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Water quality changes in a salt water system adjacent to south San Francisco Bay

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WATER QUALITY CHANGES IN A SALT WATER SYSTEM ADJACENT TO SOUTH SAN FRANCISCO BAY

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ABSTRACT

WATER QUALITY CHANGES IN A SALT WATER SYSTEM ADJACENT TO SOUTH SAN FRANCISCO BAY

by Tim Gasser

This thesis examines the water quality relationships among South San Francisco Bay, Charleston Slough, a diked shallow wetland that receives its water from the bay by tidal flow, and the Sailing Lake in Shoreline at Mountain View which receives its water from the slough through a pump system. Monthly diel studies of dissolved oxygen (DO), temperature, and salinity were done as well as additional weekly monitoring to uncover the diel and seasonal cycles in water quality, to evaluate the adequacy of the regional water quality control board (RWQCB) permit testing requirements, and to ascertain what the effects on lake DO are from changing water levels and pumping schedules in the slough.

Results showed that the slough undergoes extreme diel DO fluctuations during the summer with anaerobic conditions occurring routinely in the morning due to excessive algal growth. The lake has more muted cycles but violates the 5.0 mg/l RWQCB DO standard frequently during the summer. Managing water levels in the slough apparently has little effect on DO, but a 12:00-24:00 h pumping schedule delivers significantly more oxygen to the lake than the alternative 7:00-19:00 h schedule.

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LIST OF ABBREVIATIONS

BCDC	San Francisco Bay Conservation and Development Commission
BOD	biological oxygen demand
cm	centimeters
DEIR	Draft Environmental Impact Report
DO	dissolved oxygen
ERA	Ecological Research Associates
ft	feet
gal	gallons
gm	grams
h	hours
ha	hectares
kg	kilogram
l	liter
m	meter
m^3	cubic meters
mg	milligram
ml	milliliters
MVCD	Mountain View City Datum
n.d.	no data

LIST OF ABBREVIATIONS (continued)

NGVD	National Geodetic Vertical Datum
$^{o}/oo$	parts per thousand
PARWQCP	Palo Alto Regional Water Quality Control Plant
RWQCB	Regional Water Quality Control Board
SBDA	South Bay Dischargers Authority
SCVAS	Santa Clara Valley Audubon Society
SEL	Scientific Environmental Laboratory
USEPA	United States Environmental Protection Agency

CHAPTER 1

INTRODUCTION

This study examines the water quality relationships among 3 bodies of water: South San Francisco Bay, a natural body of water; Charleston Slough, a modified body of water; and the Sailing Lake in Shoreline at Mountain View, City of Mountain View, County of Santa Clara, California, an artificial body of water (Fig. 1). Charleston Slough is a diked shallow wetland which receives its water from the bay from tidal flow through a culvert. The lake, located adjacent to a former landfill, receives its water supply from Charleston Slough through a pump and pipe system. Water flows out of the lake into a box weir and through a culvert to Permanente Creek and Mountain View Slough and then out to the bay (Fig. 2, the map of the study area, is in an envelope on the back cover). Thus the entire system provides an unusual opportunity to study the interactions between a large natural system such as an estuary and the artificial environments created from it, in which the attempt is made to utilize natural forces along with human energy systems to create a system which will be sustainable over long periods of time. Odum et al. (1963, 374) defined "ecological engineering . . .. as environmental manipulation by man using small amounts of supplementary energy to control systems in which the main energy drives are still coming from natural sources."

San Francisco Bay provides a diverse and productive ecosystem supporting critical wildlife resources as well as many important economic

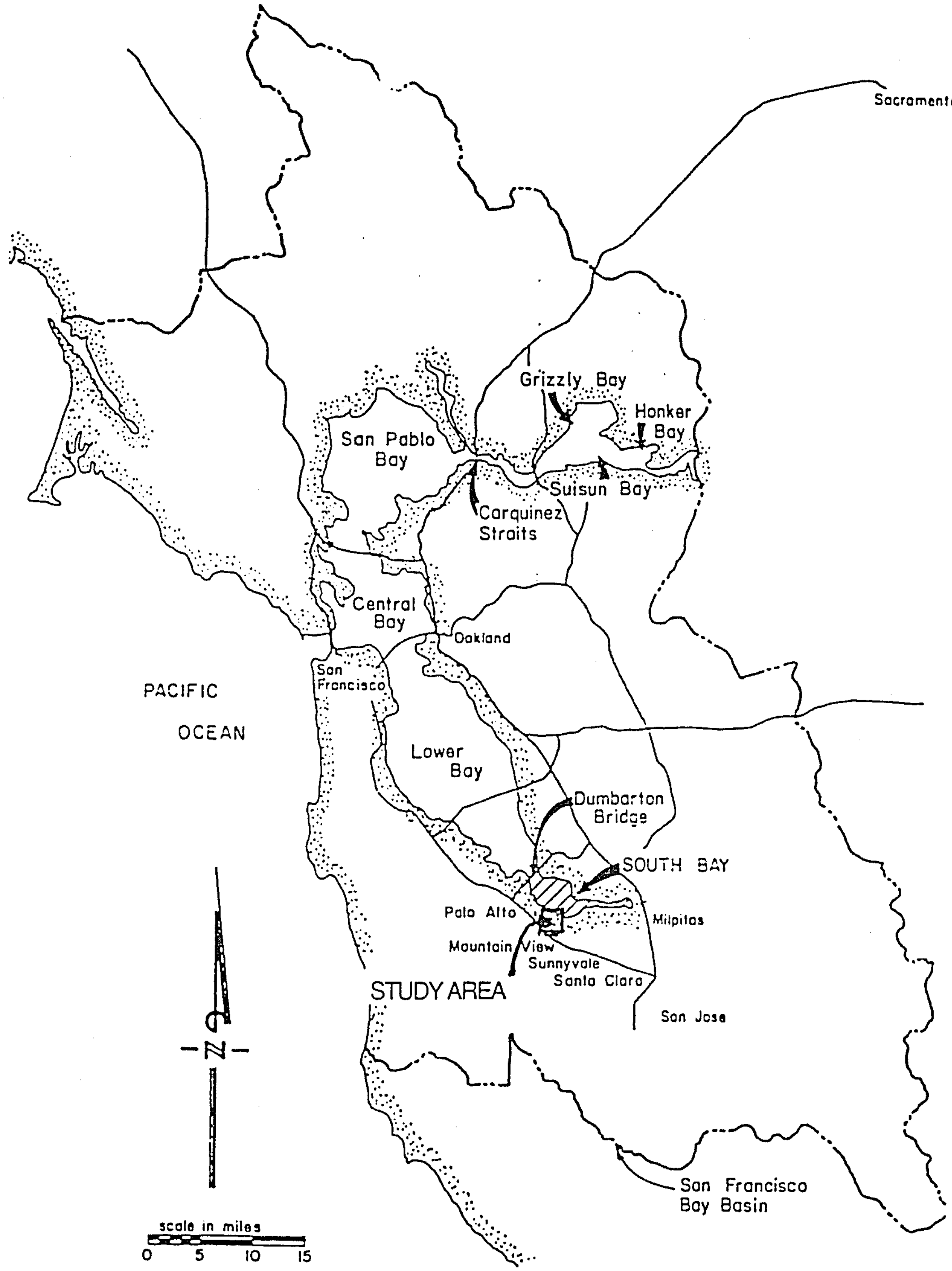

Fig. 1. Map of San Francisco Bay. Study area is marked with square at Mountain View in South Bay. Adapted from Larry Walker Associates, Inc., and Kinnetic Laboratories, Inc., SBDA Water Quality Monitoring Program: Final Technical Report: December, 1981-November, 1986, SBDA (San Jose, 1987).

activities including fishing, shipping, industry, agriculture, recreation, and tourism. This system is threatened by a number of problems including intensified land use, the decline of biological resources, and increasing pollution. The San Francisco Estuary Project, created under the authority of the federal Clean Water Act, recognizes the need for long term monitoring programs and basic research on the bay in order to increase the knowledge on which management decisions are made (Monroe and Kelly 1992).

Some long term studies of the southern reach of San Francisco Bay have been completed in recent years such as the 5 year study sponsored by the South Bay Dischargers Authority (SBDA) to document the effects of the 3 South Bay water treatment plants on the water quality of the bay (Stevenson et al. 1987). A water quality study was done at the Cargill (formerly Leslie) Company salt ponds near Alviso at the southern end of the bay which include environments similar to Charleston Slough (Lonzarich 1989). A short term water quality study of the Shoreline system was completed in 1984 (Axler, Goldman, and Reuter 1984) which demonstrated that the water quality of the system seemed to be satisfactory at that early stage of its existence. Since 1986 monthly water quality measurements have been done to comply with the permit obligations of the California Regional Water Quality Control Board, San Francisco Bay Region (RWQCB). This testing, however, did not use diel (making measurements of water quality parameters over a 24 hour period) methods for measuring changes in oxygen over the course of a day. The diel oxygen curve method has been used to measure community oxygen metabolism in rivers (Odum 1956), estuaries (Odum and Hoskin 1958; Kenney et al. 1988), fresh water lakes (Ganf and Horne 1975) and marine fish ponds

(Erez, Krom, and Neuwirth 1990). This study uses diel oxygen curve measurements in a new way to measure oxygen inflows to the Sailing Lake from Charleston Slough via the pumping system.

Artificial circulation systems and their impacts on temperature stratification and oxygen levels in lakes have been studied extensively but the focus has mainly been on freshwater lakes (Pastorok, Ginn, and Lorenzen 1981; Johnson and Davis 1981; Henderson-Sellers 1984). In this study the effect of an artificial circulation system on a salt water lake is investigated.

Background Regarding Charleston Slough

Charleston Slough, located between the Palo Alto Flood Basin and Cargill Salt Pond A1, is divided into 2 sections called the outer and inner slough. The outer slough, outside the levee which has the culvert, is subject to complete tidal action. The inner slough, totally surrounded by dikes, only receives bay water through the culvert at high tides. There is very little tidal exchange at low tides. Charleston Slough was a part of the historic tidal marshlands of South San Francisco Bay. Since 1921 it has been diked, but until 1975 it was still a vegetated salt marsh subject to partial tidal action. At that time the inlet/outlet pipe connecting it to the bay was replaced with a smaller one at a higher elevation. This caused the inner slough to turn into a shallow pond drowning up to 60 acres of vegetation, and there was no longer a significant tidal exchange (about 0.1 ft/day). Subsequently, the Leslie Salt Company gave the slough to the City of Mountain View which planned to use it for the water supply to the Sailing Lake (LaRiviere and LaRiviere 1984, iii).

The San Francisco Bay Conservation and Development Commission (BCDC) issued a permit in 1978 allowing the city to use the slough water for the lake. The permit included several marsh restoration requirements including establishment of a tidal fluctuation of at least 0.95 feet in the inner slough, the maintaining of wildlife values, and a projected 30 acres of restored marshland vegetation by 1988. To achieve the desired tidal fluctuation, the city replaced the pipe in the dike with a hydraulic control structure designed to control the tidal level in the inner slough in 1981. However, this structure has never worked as designed due to excessive siltation (Vandivere, Harvey, and Kelch 1988, 2-3).

Since 1984 there have been several studies (LaRiviere and LaRiviere 1984; Krone and Associates, and Cheney 1985; Vandivere, Harvey, and Kelch 1988; Coats 1989) analyzing the slough and the consequences of various alternatives for altering its water supply system in order to induce the desired tidal exchange and marsh restoration. In January 1990 BCDC issued a draft environmental impact report (DEIR) discussing the alternatives for restoring the slough to a tidal marsh habitat (BCDC 1990). However, during the time period of the study no marsh restoration work was done on the slough.

Water Level Experiment

In 1988 Shoreline tried to increase the tidal fluctuation in the slough.by adjusting the existing control structure. This action came as a result of an agreement with the Friends of Charleston Slough and the Santa Clara Valley Audubon Society (SCVAS), in conjunction with BCDC, to experiment with lowering the water level in the inner slough by about 6 to 12 inches to increase the shallow water/mudflat habitat in order to promote greater use of the slough by shorebirds. The controls on the inlet/outlet structure were adjusted 4 times over a period of about 1 month during April and May 1988 in an attempt to achieve this goal. During the remainder of 1988, there was an observed increase in the number of shorebirds using the slough. However, on several occasions the water level reached such a low level that land bridges formed, and the inlet/outlet structure was separated from the pump. When this occurred, the pump had to be turned off until the level in the slough increased again (Posternak 1988b, 3-4).

During the summer of 1988, while the water level experiment in the inner slough was in effect, the monthly data collected at the Charleston Slough pump (I-1 on Fig. 2) for dissolved oxygen (DO) indicated a decline in water quality in both the inner slough and the Sailing Lake. In early 1989 Shoreline raised the water level in the slough by adjusting the inlet/outlet structure to the setting previous to the experiment in order to raise the water level in the slough (Trulio 1989b, 2). It was assumed that raising the water level would improve the DO and return it to the pre-April 1988 level (Trulio 1989a, 3). Further adjustments at the control structure have been made periodically to maintain the water level in the slough at about the same level since that time (Trulio 1991, 4). However, as will be discussed in detail later, the subsequent monthly DO readings have not returned to the pattern they followed prior to the water level experiment.

Water Quality Testing

Because the outflow from the lake returns to San Francisco Bay via a box weir (E–1 on Fig. 2), the City of Mountain View is regulated as a discharger by the California Regional Water Quality Control Board, San Francisco Bay Region (RWQCB) in the same way that water pollution control plants are. Shoreline is required to monitor and maintain the water quality in both the slough and the lake in order to comply with its discharger permit with the RWQCB. The permit established the testing locations and the schedule of monthly testing for various water quality parameters as well as standards for the lake and the receiving waters. For the lake the DO standard is 5.0 mg/l minimum. Shoreline is required to test the DO in the lake at 3 locations once a month from November through April and twice a month from May to October (RWQCB 1986). Although not specifically required to do so by the permit, Shoreline has also measured the DO in Charleston Slough since 1986. Tests have been done on a monthly basis since 1986 by Scientific Environmental Laboratories, Inc. (SEL) of Mountain View, California, and quarterly reports which analyze the SEL data are submitted to the RWQCB by Ecological Research Associates (ERA) of Davis, California.

A study of the monthly data up to 1989 made clear that more frequent testing would be necessary in order to understand what was happening with the water quality in the system. This researcher carried out a preliminary series of measurements of several water quality parameters during the summer of 1989 (temperature, salinity, and DO) at Charleston Slough and the Sailing Lake. Several readings were taken over the course of a testing day at several different locations. Tests were done once every 2 weeks instead of just one measurement per month per testing location. These tests showed that extreme daily changes in dissolved oxygen occurred (near 0 mg/l in the early morning to near 20 mg/l in the late afternoon) in Charleston Slough. At that time the schedule for pumping water into the lake was from 7:00 to 19:00 h. As a result of what was discovered about the oxygen cycle in Charleston Slough, the decision was made to change the pumping time to begin later in the day to avoid the very low DO content of the morning hours. This change was based on the hypothesis that higher quality water from Charleston Slough would improve water quality in the lake.

Purpose of the Study

This thesis addresses several questions raised by the existing data and the results of the preliminary investigation in 1989 regarding the water quality of the Charleston Slough—Sailing Lake system.

1. What are the daily and seasonal cycles in the slough and lake water quality parameters that would be revealed by a more extensive testing program? What factors influence these cycles?

2. Is the schedule of testing required in the RWQCB permit adequate to give sufficient information on which to base analysis of water quality and subsequent management decisions for maintaining the lake system at the standards established in the permit?

3. Can the slough and lake water quality be influenced positively by the simple, inexpensive management strategies available in the system as it now exists?

a. Specifically, does increasing the water level in Charleston Slough by adjustments in the hydraulic control structure at the entrance of the inner slough have a significant impact on DO levels in the slough?

b. Does changing the pumping time to the lake have a significant effect on the amount of oxygen that is pumped into the lake?

c. How does the daily amount of oxygen pumped to the lake compare to the daily changes in the total oxygen in the lake due to all sources or sinks of oxygen?

Significance of the Project

BCDC sponsored studies of the diked historic baylands surrounding the bay in the early 1980's (Harvey et al. 1982; Madrone Associates et al. 1982) which enumerated the ecological values of diked baylands and gave guidelines for enhancement and restoration of the baylands. Environments similar to Charleston Slough are described, but the unusual Shoreline feature of a diked marsh being the water supply for an artificial saline lake by means of a pump system was not mentioned as existing anywhere in the San Francisco Bay Area at that time. The limited knowledge available about such a system limits the ability to manage the system to achieve a variety of worthwhile objectives, including salt marsh restoration, wildlife management, and water quality maintenance.

Previous studies of the system have not focused on diel changes in water quality. A greater knowledge of the nature of the seasonal and diel changes in the water quality of the system should be useful in increasing the ability to control the water quality of the present system. Adjusting the hydraulic control structure and changing the pumping schedule are such easily implemented management strategies that it will be useful to know whether they have significant impacts on water quality.

BCDC would like to alter the slough so that it is more completely subject to natural tidal action in order to achieve restoration of vegetated salt marsh habitat. This study will provide baseline data for subsequent studies of water quality in the new system. Additionally, it will provide valuable data in the effort to model the system more accurately which will increase the ability to predict the impact of changes to the system, either natural or human caused.

This study also characterizes the principal DO patterns in a shallow, ponded, saline wetland. Since the bay is lined with thousands of acres of such habitat in the form of salt ponds, this study will provide data on an important feature of the bay's environment.

CHAPTER 2

STUDY AREA

The study area is located at Shoreline at Mountain View, a 544 acre (220 ha) recreation and wildlife area built on a former sanitary landfill site adjacent to San Francisco Bay. It is owned by the City of Mountain View and was dedicated in 1983.

Charleston Slough

Inner Charleston Slough (see Fig. 2 for map of study area) has an area of about 103 acres (42 ha) and lies in the northwest corner of the park adjacent to the Palo Alto Flood Basin to the west, the Cargill (formerly Leslie) Salt Pond to the east, and the Coast Casey Forebay to the south. It is completely enclosed by dikes, but is connected to the outer slough, a fully tidal marsh open to San Francisco Bay, by a hydraulic control inlet/outlet structure (henceforth called the gate). Water flows through the gate (G–1 on Fig. 2) into the slough when the tidal level in the outer slough is higher than the level in the inner slough, but there is very little exchange of water through the gate when the tidal level in the outer slough is at or below the level inside. Thus the gate acts essentially as a one-way conduit that allows water into the slough as the tide rises and falls but does not allow much water to flow back to the bay from the slough at low tide. Excessive siltation in the conduits in the gate structure prevents water from flowing out of the inner slough at low tide (Vandivere, Harvey, and Kelch 1988, 2-3). Water is pumped into the Sailing Lake from the south end of the slough.

From 1981 to 1989, nutrient data were collected by the SBDA study and subsequently by the Palo Alto Regional Water Quality Control Plant (PARWQCP) at the PA C–R station at the head of the channel leading to Charleston Slough (Fig. 2). Consistently high nitrate and phosphate concentrations were recorded. The average nitrate concentration was 2.2 mg/l with a range from 0.04 to 18.5 mg/l. The average phosphate concentration was 3.8 mg/l with a range of 0.5 to 22.1 mg/l (Stevenson et al. 1987; PARWQCP 1987-1989).

Slough Habitats

The environmental consulting firm of Harvey and Stanley Associates prepared a list of the habitats occurring in the inner slough as of September 1988 (Vandivere, Harvey, and Kelch 1988). On the upper slopes of the levees there were 5 acres (2 ha) of upland/transitional vegetation. The endangered California least tern is known to favor the levee between the slough and the salt pond as a roosting area.during the post-breeding season (Posternak 1988b, 1). The muted tidal action supports 10 acres (4 ha) of pickleweed marsh. There were about 3 acres (1.2 ha) of tidal pickleweed-cordgrass marsh. This habitat will support the salt marsh harvest mouse and the California clapper rail which are both endangered species. These are the habitat types that BCDC expected would cover at least 30 acres (12 ha) by July, 1988. Historically, there was a deep water channel (more than 2 ft deep) in the slough which is still shown on maps of the slough. Because of siltation since 1976, this habitat was less than 10 acres and possibly 5 acres or less. The channel provides good foraging for both the Forster's and least terns. Mudflat/shallow water (less than 2 ft deep) makes up the rest of the slough area. The ratio between mudflat and shallow water varies according to the level of the water, but the maximum mudflat area under the 1988 conditions was less than 5 acres. Mudflat/shallow water supports many bird species including shorebirds, wading birds, and ducks. The water level experiment in 1988 exposed an additional 2 to 3 acres of mudflats which likely would have transformed naturally into additional marsh area if they had been left exposed (Vandivere, Harvey, and Kelch 1988, 3–7). In an annual summary report on conditions at Charleston Slough for 1990 Trulio (1991) found that there had been no change in plant abundance or diversity during the year. No significant change in habitat types is expected until tidal fluctuation is increased.

Slough Fish

A study of the fish in the slough found that in August 1989, 95% of the 1327 fish caught were rainwater killifish (*Lucania parva*), a species tolerant of stressful conditions. Other species found in the slough in small numbers were topsmelt (*Atherinops affinis*), threespine stickleback (*Gasterosteus aculestus*), cheekspot goby (*Ilypnus gilberti*), longjaw mudsucker (*Gillichthyes mirabilis*), and yellowfin goby (*Acanthogobius flavimanus*; Phelps 1989).

Lake Supply Pump

The pump which supplies water to the lake is located on the south end of the slough (I–1 on Fig. 2). It normally operates 12 hours per day at a rate of 11,000 gallons (42 m^3) per minute which means that about 8 million gallons (30,000 m^3) per day is pumped into the lake. Using an estimate of the volume of the slough of 100 ac-ft (120,000 m^3), the water residence time in the slough is about 4 days.

Seasonal Conditions

Winter. During the winter (November to March) the slough is clear of macroalgae, but the water clarity decreases due to increased phytoplankton. Winter air temperature lows during this study ranged between 2 and 10 ºC while the afternoon highs ranged between 8 and 19 ºC. Winds are generally lighter during the winter than in the summer except under stormy conditions and are variable in direction. Rainfall is normal only during the months from November to April. However, during the time of this study there was an extended drought in California, so rainfall was lower than average every year from 1987 to 1991.

Spring-Summer. The heavy nutrient loading from South San Francisco Bay results in macroalgal blooms which begin to appear during the spring and build up into heavy algal mats which cover a good deal of the slough during May through July. These mats consist of *Ulva* (sea lettuce) and *Enteromorpha* (Phelps 1989). They begin to decay during July and have mostly disappeared by the end of August. Water clarity increases during the summer as the macroalgae becomes dominant. Between April and October air temperature lows varied between 9 and 21 ºC while the highs ranged between 19 and 24 ºC. During the summer there is often a cloud cover in the early morning which burns off by mid-morning. The prevailing winds are from the northwest and are typically light in the morning increasing to a strong breeze by late afternoon and then dying down again by sunset.

Sailing Lake

The west end of the lake is about 300 m east of the pump in Charleston Slough. The lake has an area of about 50 acres (20 ha) and a mean depth of about 17 ft (5.2 m). The lake capacity is about 850 ac-ft (1.1 million m^3). The residence time is about 37 days.

The pipe into the lake extends along the bottom into different sections of the lake and has outlets at 4 different positions (marked on Fig. 2), so the water is well-circulated in the lake. Most of the flow enters at the first outlet about 100 m from the dock at the west end of the lake where one can see a strong welling up at the surface when the pump is on. There is a less noticeable disturbance at the surface of the second outlet, and no noticeable disturbance at the subsequent outlets.

The bottom has a clay layer between it and the adjacent former landfill site on the lake's south side where the golf course was built. The water drains out the southeast end of the lake through a box weir, which keeps the lake level very constant. A pipe carries the water underground for 150 m where it drains into Permanente Creek. From there the water flows through Mountain View Slough and back into San Francisco Bay.

Testing Locations

For the purposes of this study, 4 of the locations specified in the RWQCB permit for monthly water quality testing (RWQCB 1986) were utilized as test sites. There are 3 stations in the lake. The SML–1 testing station is on the east side of the lake at the end of the boat dock nearest the boathouse built in 1991 to serve the recreational users of the lake. The SML–2 station is at the end of the small dock at the west end of the lake. The third testing station (E–1) in the lake is at the box weir lake outlet. The fourth station (I–1) is at Charleston Slough in the channel leading to the lake supply pump.

In addition to the above locations, readings were taken once or twice a month on the bay side of the gate (G–1) to get an indication of the quality of the incoming bay waters. A series of readings were taken in the summer of 1989 from a canoe at an open water location (O–1) near the middle of the slough and nearby locations with heavy algal mats (A–1). All of these stations are marked on Fig. 2. Also shown on Fig. 2 is the PA C–R station used by the PARWQCP during the 1980's to monitor receiving bay waters. The PA C–R station is at the entrance to the channel leading to Charleston Slough. Data from this station is cited to indicate the history of water quality in bay waters during the 1980's.

CHAPTER 3

METHODS

Measurement of Seasonal and Daily Cycles in Water Quality

Field measurements were designed to uncover seasonal and daily cycles in water quality and changes that occur as water passes through the system. There were 3 phases of the field testing which began in May 1989 and continued through December 1991 as described below.

Phase 1: Characterization of Influences on DO, Temperature, and Salinity in Charleston Slough and the Sailing Lake (May 1989-September 1989)

In order to gain preliminary knowledge of what factors such as tidal cycles, photosynthesis-respiration cycles, algal mats, and pumping schedules influenced DO, temperature, and salinity as water passed through Charleston Slough and into the Sailing Lake, data were collected at several locations in the slough and the lake: outside and inside the gate (G–1), in the middle of the slough in open water (O–1) and in heavy algal mats (A–1), and at the lake supply pump (I–1) in Charleston Slough, and SML–2 and E–1 in the lake.

Gate (G–1). During June and July 1989, readings were taken on the outside and then on the inside of the gate on 4 occasions, twice at low tide and twice at high tide. During 2 days in July 1989 readings were taken at both the high and the low tides on the bay side of the gate.

Mid-slough (O–1 and A–1). From the end of June until the middle of September, on 3 dates 2 or 3 rounds of measurements per day were made at O–1 and A–1 between 6:00 and 16:00 h. During one 24 hour period 5 rounds of tests were done at these locations beginning in the evening.

Lake supply pump (I–1) and in lake (SML–2 and E–1). From May to August 1989 measurements were taken on 3 dates during the course of the day at 2 to 3 hour intervals while the pump was on. On the first date of testing, both I–1 and E–1 were tested. On the subsequent dates only I–1 was tested.

On August 27–28 and August 31-September 1, diel studies were done at the pump (I–1), and at SML–2 and E–1 in the lake. Beginning near dawn, 12 sets of readings were taken at 2 hour intervals .

Phase 2A: Daily Cycles and Effects of Changes in Pumping Schedule (September 1989-January 1990)

Up until the time of the diel testing the pump was turned on daily between 7:00 and 19:00 h. Shortly after these tests the pumping times were changed to begin at a later time. From September 1989 to November 1989 the pump was turned on between 9:45 and 12:15 h for a 12 hour period depending on the availability of park personnel. In November 1989 a timer was placed on the pump switch to shut the pump off automatically at midnight.

In order to determine the seasonal changes in the daily cycles in DO and temperature of water pumped into the lake, and the effects of changing the pumping schedule on the amount of oxygen pumped into the lake, from September 1989 until January 1990 testing at I–1 was done on a biweekly basis with 6 to 8 rounds of testing per day beginning at about 7:00 h at a

2 to 3 hour interval until the pump was turned off in the evening. In the lake 5 to 7 rounds of testing were done on the same dates at 1 or 2 of the 3 stations. Generally only I–1 was tested on the last round for each date at about the time the pump was turned off. The results from phase 2A will subsequently be referred to as all day tests in order to distinguish them from the diel tests described below under phase 2B.

Phase 2B: Diel Studies (March 1990-July 1991)

To characterize more fully the nature of the daily cycles of DO and temperature in the water being pumped into the lake as well as the cycles in the lake itself and to obtain more data on the effect of pumping schedules, the all day testing was modified to a diel basis but on a less frequent schedule. From March 1990 until October 1990, once a month a set of diel tests was done according to the following schedule. Beginning between 7:00 to 8:00 h, 8 sets of tests were done at 3 hour intervals always starting at I–1 and then proceeding to the SML–2 station. From March through May, the third stop in each round was at E–1. From June to August, the third stop was at the SML–1 station. In September and October, all 3 stations in the lake were done each round. During May and July 1991, diel tests were completed following the same schedule as for September and October 1990.

During March 1991 an opportunity arose to examine what differences in the diel cycles might occur when the pump was not operating as usual. On March 5, 1991 the pump went out of commission and was off for 8 days while repairs were completed. On March 8–9, 1991 a diel set of tests at I–1 and the

3 stations in the lake was done according to a schedule similar to that explained above except that the eighth round that would have started at 4:00 h on March 9 was omitted, and instead a round was done later between 9:40 and 11:30 h Additional single readings were done each day from March 11–14 at I–1 during the morning.

Phase 3: Weekly Testing (January 1990-December 1991)

In order to gain more frequent data on seasonal changes in Charleston Slough and the Sailing Lake, and to test the adequacy of the monthly testing schedule required in the RWQCB permit, a weekly schedule of testing was implemented beginning in January 1990. In addition to DO, temperature, and salinity which had been measured from the beginning, pH and Secchi depth readings were included for this set of data. One set of measurements was taken at I–1 between 8:00 to 9:00 h when the pump was off. Then, during the rest of the morning 1 set of measurements was made at each of the 3 stations in the Sailing Lake. Beginning in August 1990, a second set of DO, temperature, and salinity measurements were made at I–1 in the early afternoon after the pump was turned on in order to provide more data on the changes to the water since the morning reading.

In order to detect seasonal variations in the water quality of water coming into the slough, DO, temperature, and salinity were measured near the time of high tide on the outside of the gate beginning in April 1990 and continuing through 1991 once every 2 to 3 weeks. Readings were generally made in the early afternoon but were occasionally done during the morning. These measurements were done in conjunction with the weekly tests described above.

Equipment and General Techniques

Salinity, DO, and temperature were measured at every round of testing at every location. Secchi depth and pH were measured at each location during the weekly testing. Weather conditions were recorded on every round as described below.

Salinity readings were measured with the YSI Model 33 S–C–T meter according to the instructions given in the manual for the instrument. Initial measurements of the water column at 0.5 m intervals at G–1, I–1, and all the lake stations during the summer of 1989 showed little or no variation in salinity top to bottom, so subsequently only a single measurement of salinity was made at these stations for each time at about a depth of 1 m. The meters were tested for accuracy with a NaCl solution (10 $^{o}/oo$) periodically, and cleaned and/or replated according to the directions in the manufacturer's manual when necessary.

For DO measurements YSI Models 51A, 54, and 58 meters were used at different times depending on the availability of equipment. With the 51 and 58 models the DO reading is obtained directly from the meter after the salinity dial is set to the reading obtained from the salinity meter. With the 54 model the actual DO value must be calculated from the observed value using the formula for salinity correction given in the instruction manual. The air calibration method given in the instruction manuals for each model was used. Readings were taken of the water column at 0.5 m intervals from just below the surface to near the bottom with an additional reading as close to the bottom as possible (without putting the probe into the substrate) following the instructions in the manuals, taking care to keep the probe moving, and waiting until a stable reading was obtained at each depth. Beginning in October 1989, the water column DO profile was measured twice at each time at each location. The DO values used in all graphs and calculations are the means of the 2 readings at each depth.

The water temperature was measured at the same depth intervals at which the DO was.measured. Two measurements of the temperature water column were taken during October and November 1989, but normally no difference was found between the readings at a particular depth. Subsequently, only 1 reading was taken at each depth.

The Secchi depth was measured using a standard sized (20 cm diameter) disk once per sampling day at each location tested. The disk is lowered in the water column until it disappears and then is raised until it reappears. The Secchi depth is the average between these depths measured to the nearest 0.1 m.

An Orion Model 230 pH meter was used to measure the pH near the surface following the 2 buffer calibration procedure given in the instruction manual.

The air temperature was recorded at each station at each time, and qualitative observations were recorded about the weather conditions including degree of cloudiness and wind direction and wind intensity. Observations of any floating matter, algae, or unusual conditions in the water column were recorded.

At the I–1 and G–1 stations in Charleston Slough the water level from the staff gauges was recorded at each time.

Percent Saturation Calculation

Percent saturation of DO is obtained by dividing the actual DO by the saturation DO concentration for the same temperature and salinity as the observed value and multiplying by 100. Weiss (1970, 727) gives a formula for calculating saturation DO in ml/l. This is converted to mg/l by multiplying by 1.4277 (Bowie et al.1985, 91). In this formula temperature is in ºK and salinity is in $^{0}/oo$. Pressure is assumed to be constant at 1 atmosphere. The values obtained with this equation agree closely with the American Public Health Association's Standard Methods for the Examination of Water and Wastewater (sixth edition) tables for both fresh and sea water (Bowie et al. 1985, 96–99).

Evaluation of Adequacy of Monthly Testing Schedule

To evaluate whether the monthly testing schedule specified in the RWQCB permit was adequate to characterize the seasonal variations at the pump and in the lake, the weekly data collected during 1990 and 1991 were compared to the monthly data obtained from the ERA quarterly reports for the same stations between the same dates. Because of differences in methods of data collection as well as other concerns discussed more fully in Chapter 5, only the comparison of the sets of data collected at E–1 are reported.

Evaluation of Management Practices

Water Level Management

To test the possible effects of changing water levels in Charleston Slough on DO and temperature in Charleston Slough, water level data from the staff gauge at I–1 collected from various sources was compared to the DO and temperature data from the monthly and weekly testing to see if any correlation was evident. The data were divided into periods before, during, and after the 1988 water level lowering experiment described earlier. However, statistical analysis of the data was difficult because the data from other sources were not collected with the idea of answering this question. In using the water level for this analysis, it is assumed that the volume of the slough varies directly with the water level. Recent surveys of the slough have shown little change in elevations of the bottom of the slough since 1988 (Harrison, Teasley, and Assoc., Inc. 1990).

Calculation of Amount of Oxygen Pumped from Charleston Slough to Sailing Lake (P)

In order to test the hypothesis that changing the pumping time increases the amount of oxygen delivered to the lake, estimates of the amount of oxygen being pumped per day under the different pumping schedules are required.

The Igor computer program (from Wavemetrics) has an "areaxy" function which calculates the area under an x–y graph with unequally spaced data using the trapezoidal rule of integration (Hutchinson 1990). For each round of testing for each date of all day and diel testing, the area under the depth (in m) versus the actual DO profile (in mg/l) was calculated. The result was divided by the depth to give a value for DO in mg/l over the entire water column. These values were plotted against the times of testing. The area under this curve was calculated for the following times: first, from 7:00 to 19:00 h or for the 12 hour period from the earliest time tested after 7:00 h which was never later than 7:45 h; second, from 12:00 to 24:00 h if testing was done until after midnight; and third, for the actual hours of pumping for that date. These results (in units of mg•h/l) were multiplied by the volume of water pumped per hour in l/h, which was calculated from the pump's rating and assumed to be constant at 2.5×10^6 l/h for all dates, and divided by 10^6 mg/kg to give estimates of the oxygen pumped to the lake per day (P) in kg for the different pumping schedules.

Model for Accumulation of a Substance in a Lake Applied to Oxygen in the Sailing Lake

To obtain estimates of the relative contributions of oxygen to the lake from the pump inflow as opposed to photosynthesis and reaeration, Chapra and Reckhow's model (1983, 18) for the accumulation of a substance in a completely mixed lake in a certain time was adapted for use in the Sailing Lake.

According to their model, the accumulation (ΔA) of a substance in a lake is

$$\Delta A = I - O \pm \Delta R$$

where I = inputs to the lake during a given time period, O = outputs from the lake during the time period, and ΔR = change due to reactions producing or consuming the substance within the lake. For oxygen accumulation during a certain time period in the Sailing Lake at Shoreline the formula can be adapted to

$$\Delta A = P - W \pm \Delta D \pm \Delta R$$

where P = oxygen in the incoming water from the pump during the time period, W = oxygen leaving the lake in the weir outflow during the time period, ΔD = change due to oxygen exchange with the atmosphere which is positive if the lake is undersaturated and negative if the lake is supersaturated, and ΔR is as above. Photosynthesis is the primary reaction that adds oxygen to the lake, and various processes consume oxygen including respiration of plant and animal life, decomposition, and chemical oxidation (Goldman and Horne 1983, 96). Inputs from runoff are considered to be negligible. For the purposes of this study ΔD and ΔR are considered together as 1 quantity ($\Delta(D + R)$). Rearranging the above equation yields an expression for $\Delta(D + R)$, the sum of the sources of oxygen other than P. The equation is

$$\pm \Delta(D + R) = \Delta A - (P - W).$$

Because estimates of ΔA, P, and W can be calculated using the data collected during phases 2A and 2B, an estimate of $\Delta(D + R)$ can also be calculated to compare with the other quantities.

Amount of oxygen in the sailing lake at any given time (A). Because SML–1 and SML–2 are the deeper water stations in the lake, it was judged that combining data from them would give the best approximation of the oxygen in the lake as a whole at any given time. For this reason calculations of A for each round of testing were done only for dates when testing was done at both of these stations. A method of cutting the lake into slices was devised (as shown in Fig. 3) in order to obtain estimates of the oxygen in each slice which were then summed to obtain an estimate of the total oxygen in the lake as described below.

The "disc" method of integration for a volume of a solid of revolution (Protter and Morrey 1963, 482–4) was used to calculate the volumes of slices of the lake using the following assumptions: (1) vertical cross sections of the lake

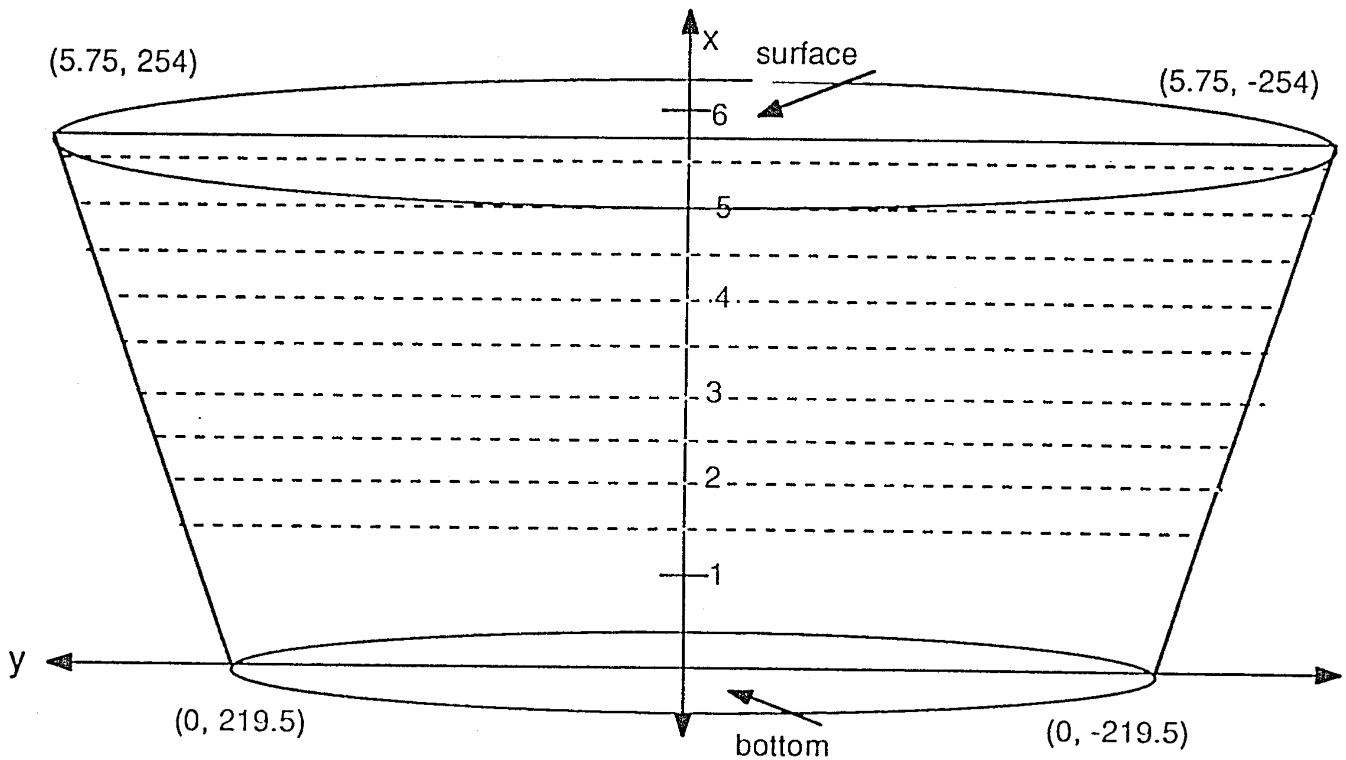

Fig. 3. Volume of solid of revolution drawing for volume of slice calculation. Drawing is not to scale. The line $y = 6x + 219.5$ is rotated around the x-axis from $x = 0$ to $x = 5.75$ to obtain the volume. Dashed lines represent slices which are 0.5 m thick except for the top one which is 0.25 m thick and the bottom one which is 1.5 m thick.

were assumed to be trapezoidal, (2) the depth of the center of the lake is assumed to be constant at 5.75 m (as measured on July 16, 1990), (3) the lake is assumed to be circular with a radius of 254 m calculated from the lake's area (20 ha), and (4) the sides of the lake are assumed to slope down from the shore to the flat lake bottom at a constant ratio of 6 out to 1 down (Rogge 1991).

The lake was divided into slices as shown in Fig. 3 in order to correspond to the DO profiles as measured. The top slice is 0.25 m thick. The succeeding slices are 0.5 m thick down to 4.25 m. The bottom slice is 1.5 m thick. The volume of a slice of the lake is obtained using the following integral adapted from Protter and Morrey (1963, 484):

$$V = \pi \int_a^b (6x + 219.5)^2 \, dx.$$

The limits of integration, a and b, are the x–coordinates of the upper and lower depths of each slice as shown in Fig. 3. Using this method, the lake volume is 1.01×10^6 m^3 which compares favorably with the value of 1.05×10^6 m^3 calculated by Mark Rogge, Shoreline engineer, by another method.

The oxygen in each slice (in kg) down to 3.25 m depth is calculated by multiplying the average of the DO readings (in g/m^3) at the SML–1 and SML–2 stations at the same depth for each round of testing times the volume of that slice (in m^3) divided by 1000 g/kg. Surface DO readings are used for the top slice. The DO readings in the middle of the slice are used for the slices from 0.25 m to 3.25 m. For example, the 0.5 m DO readings are used for the 0.25–0.75 m slice. The 3.25 to 3.75 m slice uses the 3.5 m reading from the SML–1 station and the 3.1 m reading from the SML–2 station. The slice from 3.75 to 4.25 m has only the 1 reading from the SML–1 station, and the slice from 4.25 m to the bottom uses only the 4.3 m reading from the SML–1 station. The total oxygen in the lake (A) is obtained by summing the slice values.

Change in A during a given time period (ΔA). The change in total oxygen in the lake corresponding to the approximate hours when photosynthesis was occurring was computed by finding the difference between A for the earliest round of testing in the lake (7:30–8:30) and A for the round of testing 12 hours later (19:30–20:30 h). This quantity is called ΔA_{8-20}. To compare to the 12:00 to 24:00 h pumping schedule, the A for the round closest to noon (10:30–11:30 h) was subtracted from the A for the round 12 hours later (22:30–23:30 h). This quantity is called ΔA_{11-23}. The change in total oxygen for the period of a diel testing cycle was computed by subtracting the first round's A from the last round's A for dates when diel testing was done. This quantity is called ΔA_{diel}.

Oxygen input (P) from pump to lake during ΔA time periods. Values of the actual P for the exact time periods used in the 3 sets of ΔA calculations above were calculated using the same method described above under the heading "Calculation of Amount of Oxygen Pumped from Charleston Slough to Sailing Lake (P)."

Amount of oxygen leaving lake (W). The method for calculating the amount of oxygen leaving the lake during a given period of time for dates when readings were taken at the weir outlet over the course of the day is as follows: the area under the DO-time graph between the times of interest (using surface values only) was calculated and multiplied by the volume of water flowing out the weir per hour and divided by 10^6 mg/kg. This gives a value in kg for oxygen flowing out the weir in the given time period. The volume of water flowing out was assumed to be constant at 1.2×10^6 l/h. This value is approximately half of the value per hour used for the inflowing volume of water from the pump. Because water flows out of the lake 24 hours per day and is pumped into the lake 12 hours per day, this approximation simulates the actual situation very well. Evaporation is assumed to be negligible compared to the inflow and outflow based on monthly evaporation values for South San Francisco Bay obtained from Conomos (1979, 52). For example, during July when evaporation is at a maximum, loss of water due to evaporation would be approximately 4% of inflow from the pump on an average day. When the pump is in daily operation, the water level of the lake is essentially constant, and the flow through the weir appears to be the same regardless of the time of day.

W was calculated for the same 3 time periods used in the ΔA calculation when weir data were available for those dates. In order to compare to the P values computed for the 7:00 to 19:00 h pumping schedule, W was calculated for the 12 hour period beginning at the earliest time tested at the weir. W was computed for the 12 hour period from noon to midnight to compare to the 12:00 to 24:00 h pumping schedule.

Net of input from pump and outflow from weir (P – W). For each date the net input of oxygen to the lake considering only input from the pump and outflow from the weir was computed for each pumping schedule by subtracting W from P. (P – W) was also calculated for the ΔA data to use in calculating $\Delta(D + R)$.

Net Change in Oxygen Due to D and R ($\Delta(D + R)$). An estimate of the change in oxygen due to atmospheric exchange plus reactions in the lake

($\Delta(D + R)$) for a given time period during the course of the day is computed by subtracting net actual input to the lake for that time period ($P - W$) from the change in total oxygen in the lake (ΔA) for that time period. For those dates that weir data were not available, the average of W (for the dates that W was calculated) was used in the ($P - W$) expression to obtain more values of $\Delta(D + R)$. These values are clearly marked in the results section. This was a reasonable assumption since the values of W were generally much smaller and showed less variation than the values of ΔA.

The ratio of $\Delta(D + R)$ to ΔA was calculated to obtain an estimate of the percentage increase in oxygen during the given time periods due to sources other than pumping.

CHAPTER 4

RESULTS OF DAILY AND SEASONAL TESTING

This chapter reports the results of the 3 phases of the field work conducted from 1989–91 as outlined in the methods chapter, and deals with question 1 from the introduction: What are the daily and seasonal cycles in the slough and lake water quality parameters, and what factors influence those cycles?

Phase 1 Results: Characterization of Influences on DO and Temperature in Charleston Slough and the Sailing Lake (May 1989-September 1989)

Gate (G-1) Results

High tide compared to low tide on same date. On July 2 and July 14, comparisons were done at high and low tide on the same dates at G–1. Table 1 shows the results. At high tide there is little difference in any of the parameters tested from the top to the bottom of the water column, and percent saturation is very close to 100 percent for both dates. At low tide the DO is lower than at high tide in both cases even though on the first date the low tide was in the evening, and on the second date it was in the morning. This agrees with the results of Stevenson et al. (1987, 48) for a comparable marsh in South San Francisco Bay. They did 3 diel DO studies at the Faber Tract Marsh and found that DO is at a relative maximum at high tide and at a relative minimum at low tide, regardless of the time of day of the tidal cycle.

Table 1.--Outside Charleston Slough Gate (G-1) High and Low Tide Readings on Same Dates

Date	Time	Depth (m)	Temperature (º C)	DO (mg/l)	Salinity ($^{o}/oo$)	% Saturation
7/2/89	14:40	0	25.7	7.5	25.5	106
high tide		.5	25.5	7.5	25.5	106
		1	25.2	7.3	25.5	103
		1.5	25.2	7.3	25.5	103
		2	25.2	7.1	25.5	100
		2.5	25.2	7.1	25.5	100
low tide	19:35	0	22.0	3.4	26.8	46
7/14/89 low tide	8:30	0	17.0	2.6	25.7	31
high tide	12:40	0	22.5	7.2	26.3	98
		.5	22.4	7.2	26.3	98
		1	22.4	7.1	26.3	95

Outside the gate compared to inside the gate at the same time of day. Table 2 shows the results of testing first outside the gate and then just inside the gate within a few minutes on the same date. On June 10 the testing was done at low tide during the early afternoon. The water on the deeper inside of the gate was considerably cooler (5.7 degrees difference at the surface), and DO was correspondingly higher. Also on the inside there is significant temperature stratification between 1.0 and 1.5 meters (2.6 degrees change). The temperature stratification must have occurred since sunrise because the water column near the gate is always well mixed at high tide.

The testing on July 1, 1989 was done near high tide. At this time there is little difference in any of the parameters throughout the water column both inside and outside the gate showing how well the water column is mixed when water is entering the slough.

The results at high tide on July 2 were similar to the high tide results the day before. At the low tide in the evening there was no temperature stratification inside the gate as occurred during the midday low tide reading on June 10. On July 2 the temperature was higher inside the slough than outside at low tide. The shallower water outside would cool more rapidly in the evening than the deeper water inside the slough.

The results of these tests indicate how weak the tidal influence was inside the gate once the tide went out. Under summer conditions, even near the gate, the inner slough can become stratified very quickly. The following mid-slough results confirm the lack of influence of the tidal cycle on DO and temperature daily cycles in the slough.

Table 2.--Charleston Slough Gate (G-1) Readings Outside and Inside the Control Structure on the Same Dates

Date	Time	Depth (m)	Temp (º C)	DO (mg/l)	Salinity (⁰/oo)	% Saturation
6/10/89 Outside low tide	13:40	0	28.2	2.8	25.7	41
		0.4	28.0	1.2	25.7	18
Inside low tide	13:55	0	23.5	4.5	25.7	62
		0.5	23.5	4.3	25.7	59
		1	22.8	3.3	25.6	44
		1.5	20.2	2.0	25.5	26
		1.9	18.8	1.9	25.3	24
7/1/89 Outside high tide	13:45	0.0	25.7	6.9	26.5	99
		0.5	25.2	6.9	26.5	98
		1.0	25.0	6.7	26.5	94
		1.5	25.0	6.2	26.5	88
		2.0	25.0	5.7	26.5	80
Inside high tide	14:10	0.0	25.1	8.2	26.5	116
		0.5	25.1	8.4	26.5	119
		1.0	25.1	8.2	26.5	116
		1.5	25.1	8.4	26.5	119
		2.0	25.1	8.1	26.5	115
7/2/89 Outside high tide	14:25	0	25.7	7.5	25.5	106
		0.5	25.5	7.5	25.5	106
		1	25.2	7.3	25.5	103
		1.5	25.2	7.3	25.5	103
		2	25.2	7.1	25.5	100
		2.5	25.2	7.1	25.5	100
7/2/89 Inside high tide	14:40	0	25.1	7.6	25.5	106
		0.5	25.1	7.6	25.5	106
		1	25.1	7.6	25.5	106
		1.5	25.1	7.6	25.5	106
		2	25.1	7.5	25.5	105
Ouside low tide	19:20	0	22.0	3.4	26.8	46
Inside low tide	19:35	0	24.1	3.6	26.9	50
		0.5	24.1	3.8	26.9	53
		1	24.0	3.9	26.9	54
		1.5	24.0	3.7	26.5	51
		1.9	24.0	3.2	24.0	44
		2	24.0	1.0	24.0	13

Mid-slough results

Open water compared to water in an algal mat. On June 30, 1989 a canoe was used to obtain 3 rounds of readings near the middle of Charleston Slough in open water (O–1 on Fig. 2) and in the middle of a nearby algal mat (A–1 on Fig. 2). Each round of testing was done in the same vicinity as marked on the map in Fig. 2. However, the exact location of deeper water found on the first round was not found again in the subsequent rounds. The results for the DO and temperature profiles are shown in Fig. 4a–b.

Several differences between the open water and the water in the algal mat are readily apparent.

(1) In open water there is little or no change in any of the parameters measured from top to bottom except that the temperature was 1.0 ºC cooler on the bottom than the surface at 6:45 h.

In the algae the DO was 1.8 to 4.0 mg/l less on the bottom than the surface, and the temperature was stratified except at 7:10 h. The salinity was greater on the bottom during the first 2 rounds but not on the third. These results suggest that the algae prevent the water from circulating top to bottom as it can in the open water. Also the algal canopy shades the bottom preventing much light from getting below the surface. This shading slows down the photosynthetic production of oxygen in the algae that is underneath. In the open water the bottom was clearly visible.

(2) The temperature increase during the day in the algal mat is higher than in the open water.

(3) Salinity in the algal mat was much more variable. Values ranged from 25.0 to 30.3 $^{0}/_{00}$ in the algae but only from 27.8 to 28.7 $^{0}/_{00}$ in open water.

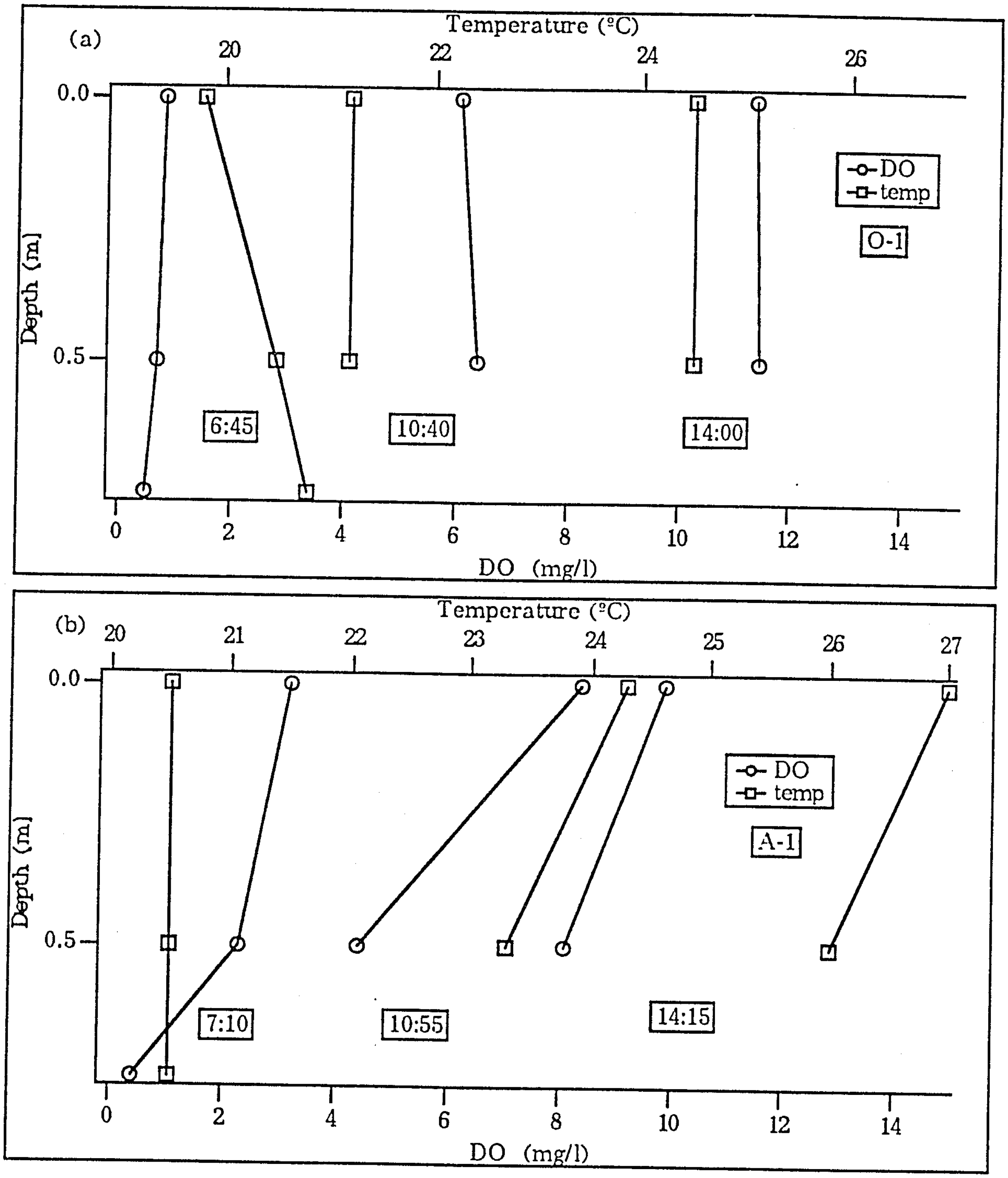

Fig. 4a-b. June 30, 1989 Charleston Slough DO and temperature profiles at (a) stations O-1 (open water) and (b) A-1 (under an algal canopy).

Circulation may also have had an impact here. The poorly circulated water under the algal mat could have a salinity gradient both horizontally and vertically.

On July 14, August 4, and August 17, similar tests were done in open water and algal mats. The data from these rounds is found in Table 3. The differences between open water and areas covered by algal canopies continued throughout the summer. In open water there was no temperature difference from surface to bottom in 10 out of 13 cases, and the average DO difference between surface and bottom was –0.2 mg/l. In the algal canopy covered area the temperature profile varied depending on the time of day. In the early mornings the temperature was the same or cooler on the surface. At all later times the temperature was cooler on the bottom. The average temperature difference from surface to bottom for the 7 later times was –2.4 ºC. The DO was lower on the bottom for all cases except one when it was the same. The average DO difference between surface and bottom was –4.3 mg/l. In canopied areas the average temperature always increased more than in open water from morning to afternoon. In both areas DO was extremely low in the early morning and increased rapidly by the afternoon. As the summer went on, the area covered by algal mats continually decreased and was restricted to shallower and shallower water. By September readings could only be done in open water.

Frodge, Thomas, and Pauley (1990) did a study at 2 small lakes in the State of Washington in which they describe similar DO and temperature effects of canopy formation by floating macrophytes. They found that dense

Table 3.--Midslough Results at Open Water Locations (0-1) Compared to Locations with Heavy Algal Canopy (A-1)

Date	Time	Depth (m)	Temp. (ºC)	DO (mg/l)	Salinity (o/oo)	Ave. Temp. (ºC)	Ave. DO (mg/l)
Open water							
7/14/89	8:00	0	19.5	2.0	27.3		
		0.5	19.7	1.2	27.3	19.6	1.6
	13:15	0	24.9	17.0	27.0	24.9	17.0
8/4/89	6:25	0	21.4	0.4	29.8		
		0.5	21.4	0.4	29.8	21.4	0.4
	12:25	0	25.1	8.3	29.0		
		0.5	25.1	8.3	29.0	25.1	8.3
	15:40	0	26.2	14.2	28.9		
		0.5	26.2	13.8	28.9	26.2	14.0
8/17/89	6:40	0	19.8	0.5	29.0		
		0.5	19.8	0.5	29.0	19.8	0.5
	12:15	0	22.3	10.7	29.3		
		0.5	22.3	10.7	29.3	22.3	10.7
	15:45	0	25.5	>17.1	28.7		
		0.5	25.5	>17.1	28.7	25.5	>17.1
Algal canopy							
7/14/89	7:40	0	18.7	0.6	28.9		
		0.3	19.0	0.6	28.9	18.9	0.6
	13:35	0	27.1	16.5	29.0		
		0.2	24.7	11.0	27.0	25.9	13.8
8/4/89	12:45	0	24.9	11.5	32.9		
		0.25	21.6	4.8	n. d.	23.3	8.1
	15:20	0	26.1	8.1	33.8		
		0.25	22.1	1.6	33.1	24.1	4.8
8/17/89	6:50	0	15.9	0.8	29.8		
		0.15	17.9	0.5	30.0	16.9	0.7
	12:20	0	30.5	8.3	30.5		
		0.15	27.0	7.2	n.d.	28.8	7.8
	16:00	0	27.1	10.1	35.5		
		0.15	25.9	5.3	37.4	26.5	7.7

macrophyte canopies partition a lake into different habitats both horizontally and vertically with distinct physical and chemical characteristics.

Pump (I–1) and Lake (E–1) Results

On May 11, 1989, 6 rounds of tests were done at the lake supply pump (I–1) in Charleston Slough and at the box weir lake outlet (E–1). The results for DO are shown in Fig. 5. They show a rapid rise in DO in the slough from the first reading at 6:10 h to a maximum at 18:10 h. At this time the DO went off the scale of the meter which means that the DO was greater than 17.3 mg/l. The percent saturation changed from an average of 59 % to greater than 220 % during this interval. On the other hand, DO at the lake outlet did not increase until after 16:00 h to a maximum at 18:40 h. The DO condition was never supersaturated as it reached a high of 92 % at 18:40 h. Salinity in the slough was always between 23 and 24 $^{o}/oo$ and in the lake between 24 and 25 $^{o}/oo$. The water temperature at the slough ranged between 15 and 21 ºC. At the lake outlet the water temperature ranged between 18.7 and 20.4 ºC. The weather conditions showed the typical summer pattern described above under study area. The large increases in DO and temperature at I–1 proved to be the typical summer pattern at the pump throughout the study.

Comparison of Mid-slough (O–1) to the Pump (I–1)

On August 3–4, 5 rounds of tests were done at I–1 as well as at O–1, including an overnight period, although no readings were taken during darkness at either location. Results for DO and temperature are shown in Fig. 6a–b. The diel cycle at I–1 was basically the same as at O–1. The only differences were that there was a greater range of values at O–1 for both

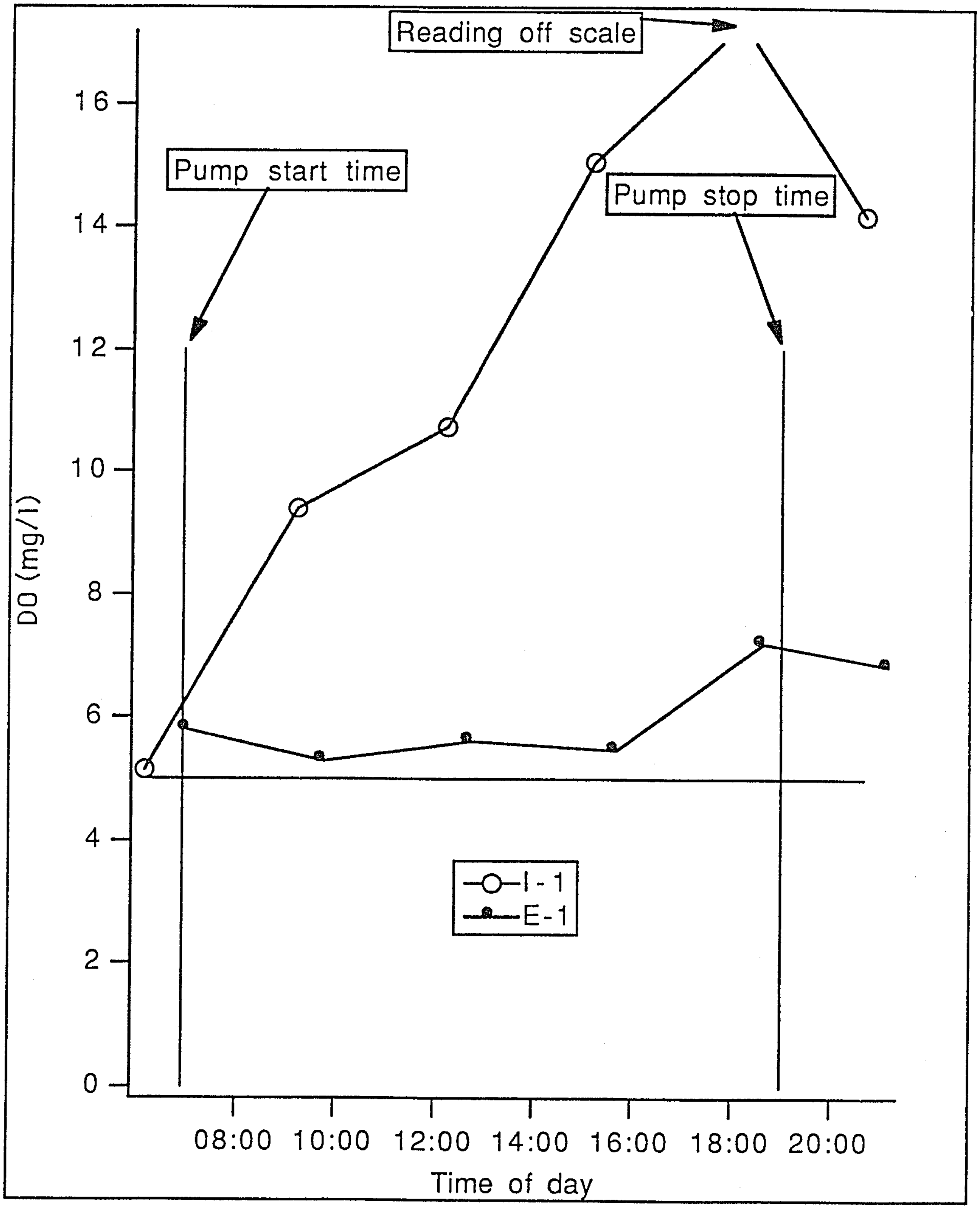

Fig. 5. May 11, 1989 DO at I-1 and E-1. Values are integrated averages of water column readings measured at 0.5 m intervals from surface to near bottom.

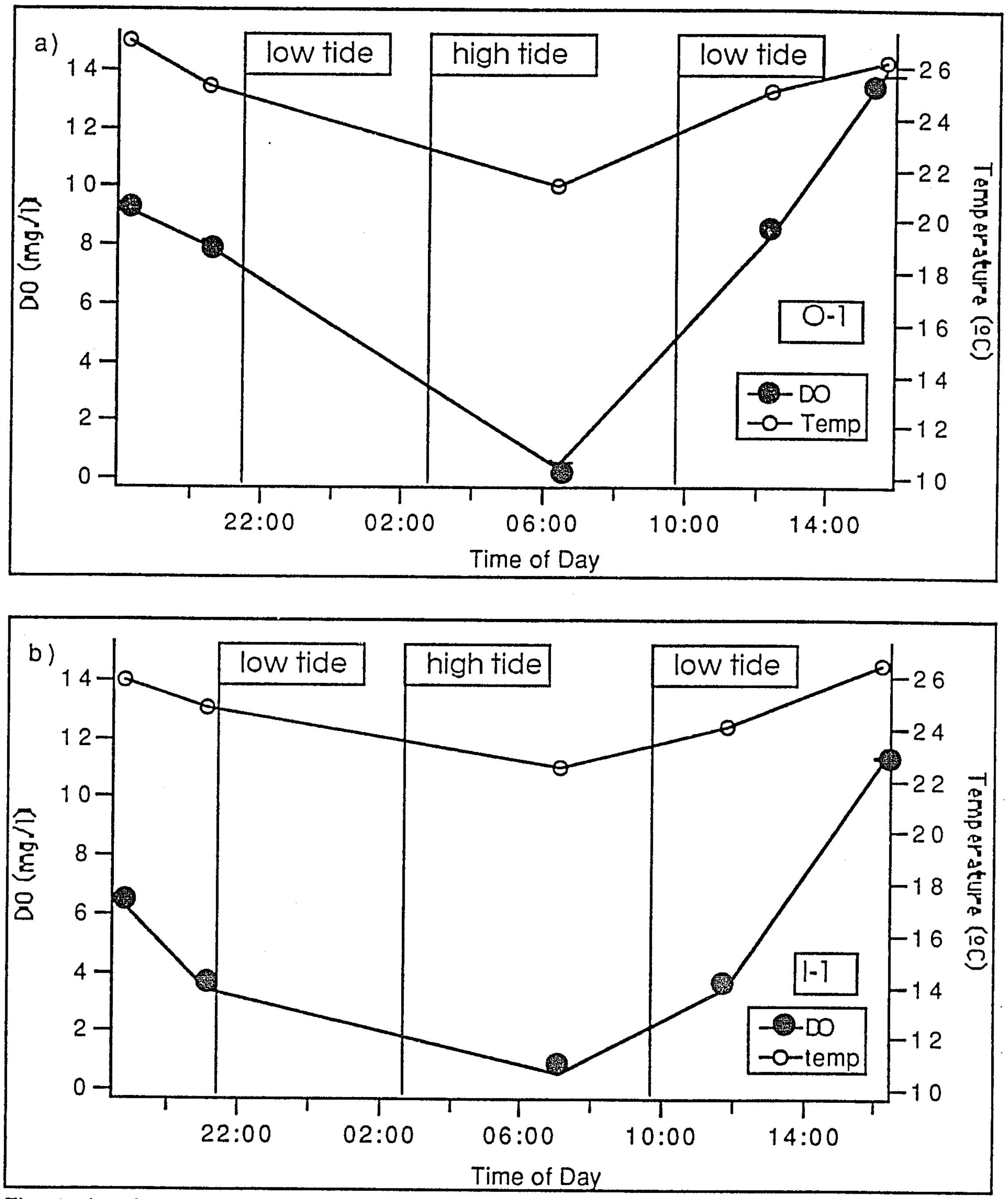

Fig. 6a-b. August 3-4, 1989 DO and temperature at a) O-1 and b) I-1. Values are averages of water column readings measured at 0.5 m intervals from surface to near bottom.

temperature and DO, and the values at O–1 were higher except that DO was almost zero in the early morning in both cases. Salinity varied little at either location. At the pump, readings ranged from 29.7 to 30.1 $^{o}/oo$, while in mid-slough the readings were from 28.9 to 29.8 $^{o}/oo$. The tidal cycle apparently had no effect on the DO cycle.

<u>Diel Testing on August 27–28, 1989 and August 31–September 1, 1989</u>

These 2 rounds of tests were the most extensive diel testing done with the shortest time interval between the dates of testing during the course of the project. In reviewing the results for August 27, 1989, it should be noted that because of a problem with the Model 54 DO meter, a Model 51A meter was substituted beginning with the fifth round of testing. However, the results apparently were not biased by this change in equipment.

<u>DO versus time of day</u>. Fig. 7a–b shows the diel changes in DO concentration for all stations tested on August 27–28 and August 31-September 1 using the integrated water column values. The horizontal line at 5 mg/l on all graphs of this type represents the RWQCB standard for the lake.

The pattern at the pump is essentially the same on the 2 dates. The off-scale readings indicate greater than 15 mg/l when using the Model 51A meter which is greater than 220 % saturation. With the pump turned on at 7:00 h extremely low DO concentration water was pumped for several hours. The sinusoidal pattern for these dates with the minimum near zero in the early morning proved to be similar for all subsequent tests done during the late summer months. The lake stations showed much more complicated cycles. Whereas on August 27 DO increased by about 2 mg/l between 6:45 and

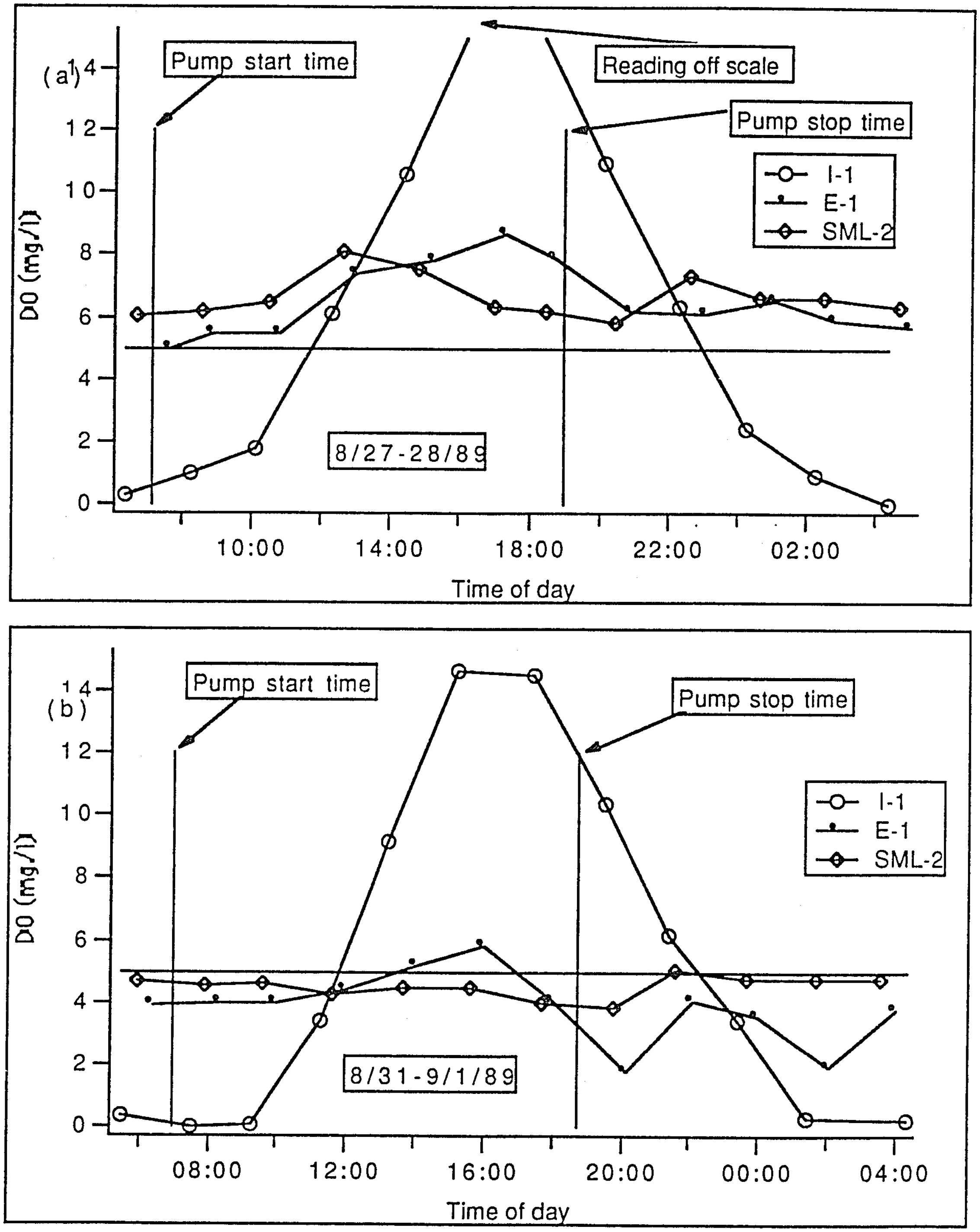

Fig. 7a-b. DO at 2 stations in the Sailing Lake and at I-1 in Charleston Slough on (a) August 27-28, 1989 and (b) August 31-September 1, 1989. Values are integrated averages of water column readings measured at 0.5 m intervals from surface to bottom.

12:40 h at the SML–2 station, no increase at all occurred in the morning on August 31. Both dates showed an unexpected increase after dark at the SML–2 station, 1.5 mg/l between 20:30 and 22:40 h on August 27 and 1.2 mg/l between 19:50 and 21:40 h on August 31. This pattern continued to occur on later dates as will be discussed subsequently. The average DO at the SML–2 station dropped from 6.5 to 4.5 mg/l during the 4 day period.

At E–1 DO increased to a maximum on both dates between 16:00 and 18:00 h, but on August 31 it dropped to unusually low values in the evening. The readings at 20:10 h and 2:05 h were the lowest recorded at the weir during the more than 2 years of readings taken during this study. The average DO at the weir dropped from 6.5 to 3.9 mg/l between the 2 dates.

The drop in DO within 4 days demonstrated that despite the steady pumping schedule which prevents the lake from becoming stratified, the oxygen content of the lake can change rather quickly. The artificial circulation provided by the 7:00–19:00 h pumping schedule did not appear to be an adequate management strategy to keep the lake above the minimum lake standard of 5.0 mg/l.

Some conclusions from phase 1. Comparing the results at the gate to those in the mid-slough area and the pump, it is clear that in the summer time the tidal cycle influences DO only near the gate. Once water is in the slough, the DO cycle is dominated by the cycles of photosynthesis and respiration resulting from the heavy concentrations of algae in the slough. In lakes most of the oxygen comes from photosynthesis, and most of the decrease in oxygen can be attributed to respiration of plants, animals, and aerobic bacterial decay

(Cole 1983, 242). The extreme daily DO cycles observed in Charleston Slough are more like those to be expected in sewage oxidation ponds than in lakes (Goldman and Horne 1983, 106).

The artificial circulation system in the lake prevents temperature and DO stratification from occurring during the summer months, and apparently impacts the lake's daily DO cycle in such a way that it is more complex than in the slough.

The results from phase 1 led to 2 of the questions that are dealt with in Chapters 5 and 6. These questions are (1) does monthly testing give agencies and managers enough information on which to base management decisions? and (2) what is the effect of the time of day of pumping on the amount of oxygen delivered to the lake?

Phase 2 Results: All Day and Diel Testing (September 1989-July 1991)

Beginning in September 1989 a systematic series of all day and diel testing dates were initiated to determine the daily and seasonal cycles in DO and temperature that occur over the course of a year and to gather data to be used in comparing oxygen delivery to the lake for different time schedules.

Phase 2A: All Day Tests from September 14, 1989 to January 19, 1990

During this 4 month period, testing was done at 2 to 3 week intervals. The tests began near 7:00 h and continued at 2 to 3 hour intervals until the pump was shut off in the evening.

Results at I–1. Fig. 8a–h shows the DO vs. time of day graphs for the 8 dates of testing at I–1. The curves for the 3 dates in September and October

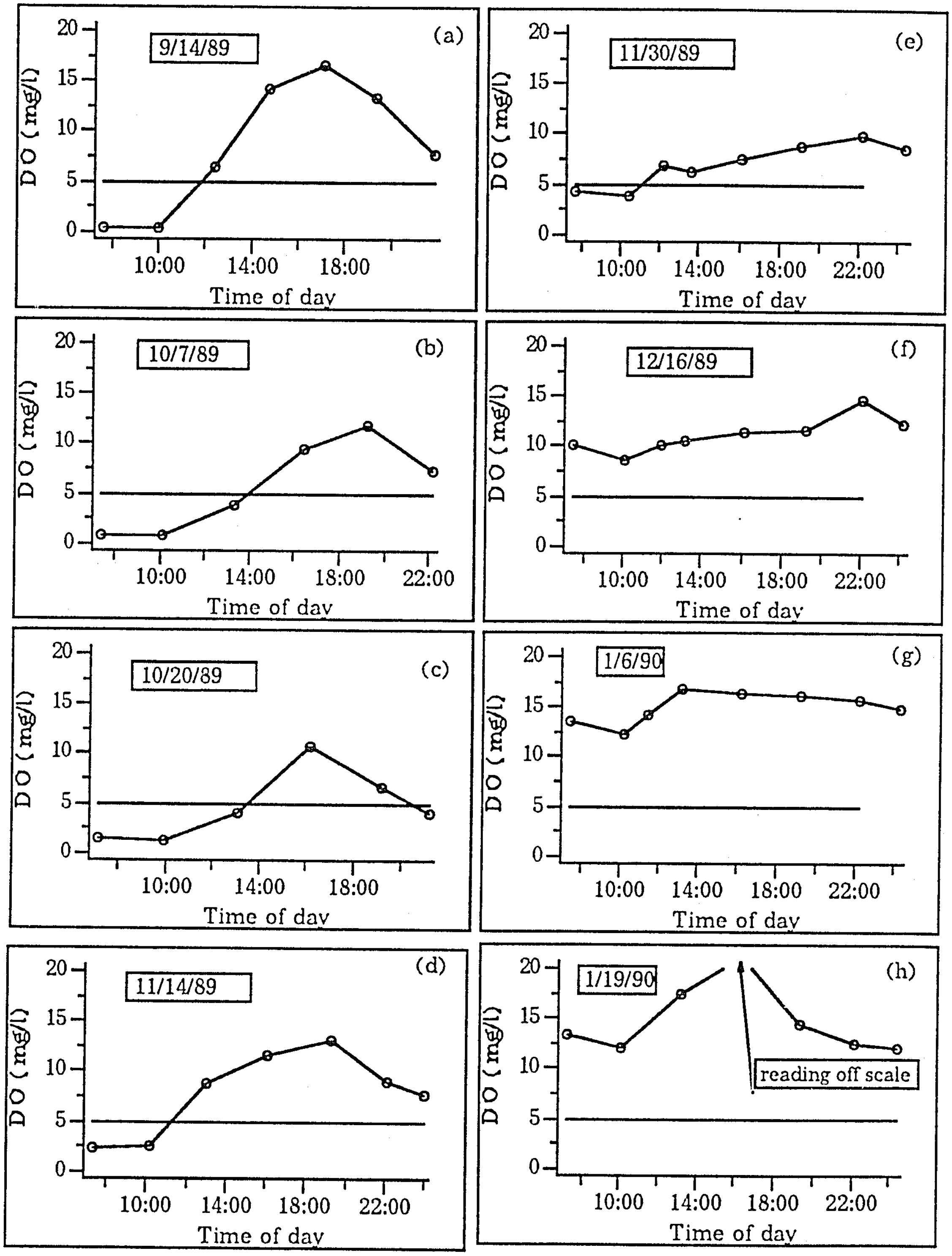

Fig. 8a-h. Charleston Slough pump (I-1) DO vs. time of day for phase 2A all day period of testing. Points are integrated averages of water column readings measured at 0.5 m intervals. Depth = 1.5 m. Horizontal line represents 5.0 mg/l standard.

show a similar pattern to the summertime pattern obtained in the phase 1 tests at I–1 (near 0 mg/l in the early morning with rapid increases in DO occurring after 10:00 h to maxima in the late afternoon and then a rapid decline after dark). Weather conditions during this period continued to be in the summer pattern with early morning low clouds, low morning air temperatures around 15 ºC and highs in the low 20's.

One negative consequence of the anaerobic conditions is the reduction of sulfates into hydrogen sulfide (H_2S) . The powerful H_2S smell makes it difficult to remain in the vicinity for extended periods of time during the late summer and fall. Bella, Ramm, and Peterson (1972, 548) state that due to the highly toxic nature of H_2S, its presence may be a more serious water quality problem than the low DO with which its production is associated.

Near the end of October, the weather began to change substantially with considerably cooler nights (lows below 10 ºC by November) and afternoon highs between 15 to 18 ºC. The November DO patterns began to show a change toward the winter pattern which was fully established by December 16. The DO minimum began to increase each date until in January, DO percent saturation was above 100 % at all testing times during the month. The winter pattern is much flatter than the summer pattern with the average DO at a much higher level. See Table 4 for temperature and DO averages at I–1, and the 3 lake stations for all dates during phase 1 and 2.

The January 19, 1990 DO curve shows that extremely high DO values can occur during the winter as well as the summer. During the afternoon on this date, a green microalgal streak was flowing into the channel leading to the

Table 4.--DO and Temperature Averages of All Day and Diel Testing at 3 Stations in the Sailing Lake and Charleston Slough (I-1)

Dates	Temperature (ºC)				DO (mg/l)			
	I-1	SML-2	SML-1	E-1	I-1	SML-2	SML-1	E-1
Phase 1—All day tests								
5/11/89	17.9			19.6	12.0			6.0
6/30/89	22.2				5.8			
8/17/89	22.8				5.9			
Phase 1—Diel tests								
8/27/89	23.4	23.1		23.5	5.9	6.5		6.5
8/31/89	23.2	22.4		23.0	5.2	4.5		3.9
Phase 2A—All day tests								
9/14/89	23.2	22.2			8.4	7.2		
10/7/89	20.7			20.5	5.6			10.6
10/20/89	18.8	18.0		19.2	4.7	4.0		4.1
11/14/89	14.9	15.1	15.3		7.9	6.6	7.3	
11/30/89	11.1	13.0	13.2		7.0	4.7	4.9	
12/16/89	9.0	10.5		11.1	11.1	6.0		6.7
1/6/90	9.7	9.3		10.0	15.0	8.1		9.6
1/19/90	10.2	10.6		11.0	14.5	7.3		7.2
Phase 2B—Diel tests								
3/9/90	14.2	13.1		13.9	10.5	7.9		8.5
4/21/90	18.7	18.9		19.6	6.9	5.8		7.0
5/25/90	20.0	19.2		19.5	6.2	6.4		6.0
6/14/90	21.6	22.0	22.6		8.4	5.6	5.9	
7/19/90	24.0	23.7	24.1		4.6	4.7	5.3	
8/20/90	23.5	23.5	23.8		5.6	4.8	5.3	
9/24/90	22.3	22.3	22.6	22.7	4.5	5.2	6.5	5.8
10/22/90	18.4	19.1	19.6	19.7	7.0	6.3	7.7	8.0
5/22/91	20.8	18.9	19.1	19.5	6.8	8.0	7.8	8.2
7/30/91	24.7	24.0	24.3	24.7	2.9	5.7	6.3	5.9

pump. Whatever the season, the extremely high DO readings were generally associated with algal blooms. However, the type of algae that is dominant changes seasonally. The heavy summertime macroalgal mats give way to microalgal species during the colder winter months.

Results in the lake. Fig. 9a–g show the DO vs. time of day graphs for the 7 dates when testing was done at SML–2. Fig. 10a–g shows the DO vs. time of day graphs for the 7 dates when testing was done at the east end of the lake. E–1 was tested on 5 dates and SML–1 the other 2 dates.

The lake stations, in general, show much different patterns than were evident at I–1. DO levels in the lake did not fluctuate nearly as much during the course of a day as at I–1, but the average DO cycled up and down at both ends of the lake from September to November between each successive date. During December and January this cyclical pattern was broken.

Although the SML–2 station showed generally less DO variation during the course of the day than at the other stations, it usually displayed a pattern of increasing DO after dark instead of the expected decrease. Possibly, this unexpected pattern is related to the currents established in the lake by the action of the pump which brings water with a higher concentration of DO to this location during the night. DO increases after dark were not normally observed at the other 2 stations in the lake.

On October 7 the maximum DO at E–1 (13.2 mg/l) exceeded the maximum at I–1 (11.9 mg/l) which was a very rare occurrence. On only one other date during the entire study did the maximum at a lake station exceed the maximum at I–1. High DO readings in the lake were associated with algal

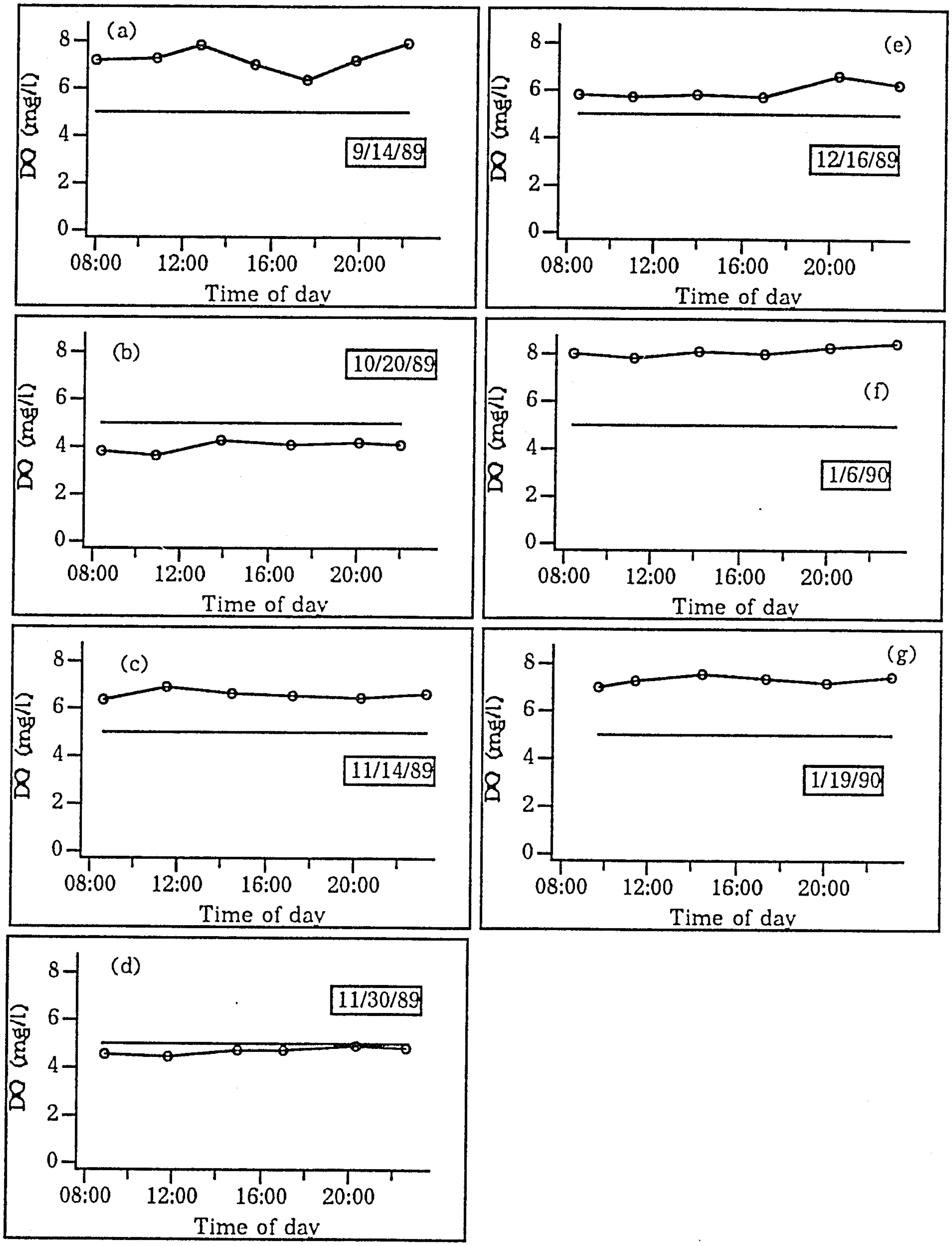

Fig. 9a-g. SML-2 DO vs. time of day for phase 2A all day period of testing. Points are integrated averages of water column readings measured at 0.5 m intervals. Depth = 3.1 m. Horizontal line represents 5.0 mg/l standard.

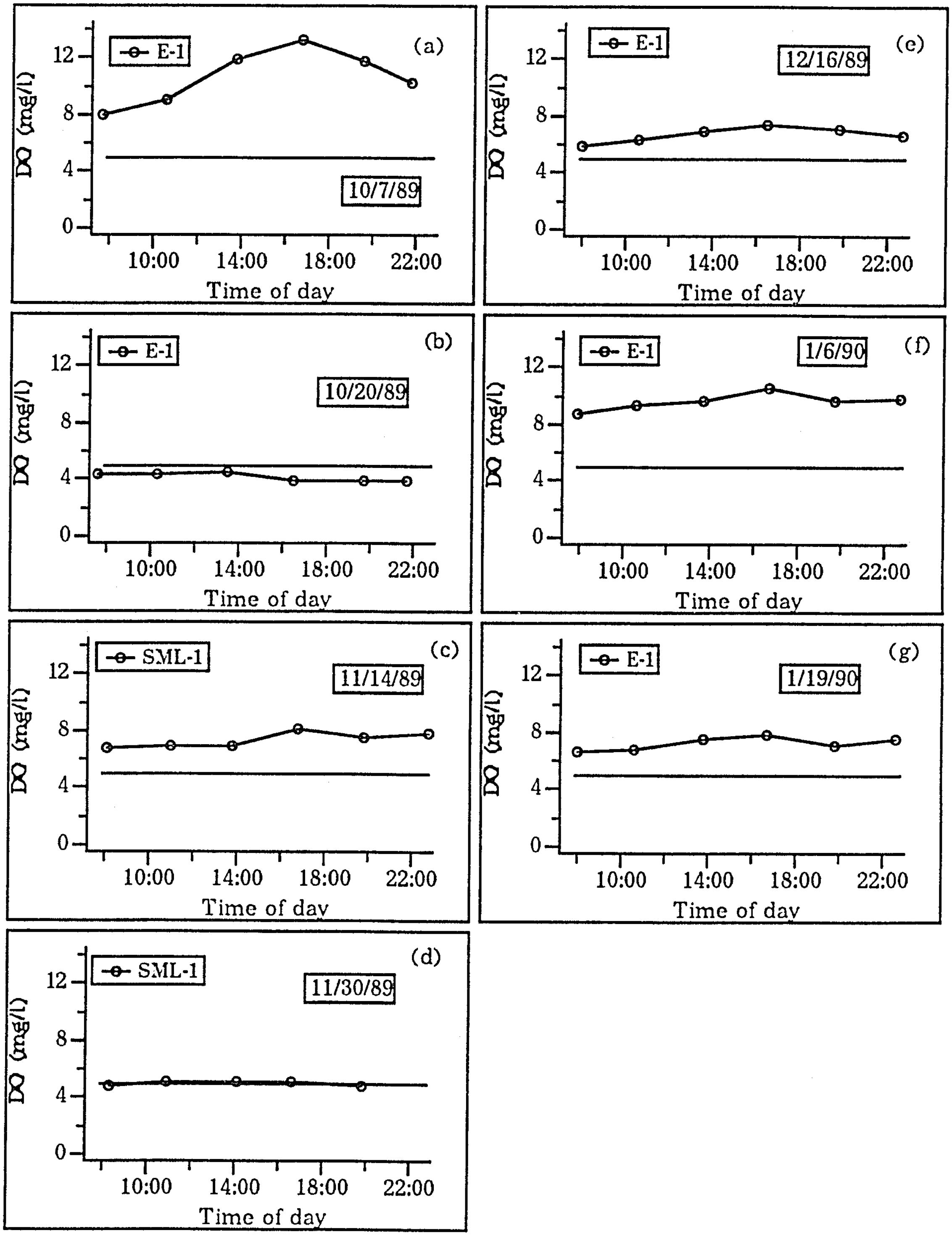

Fig. 10a-g. DO vs. time of day at east end of Sailing Lake during phase 2A all day period of testing. Points are integrated averages of water column readings measured at 0.5 m intervals. Depth = 4.3 m at SML-1. Depth = 0.9-1 m at E-1. Horizontal line represents 5.0 mg/l standard.

blooms in the lake just as they were in the slough. The large drop in average DO at E–1 between October 7 and October 20 (10.6 to 4.1 mg/l) showed how quickly the DO level in the lake could change. This result demonstrated how the monthly testing schedule could miss significant changes in the lake DO that might have an impact on wildlife. This topic is covered more fully in Chapter 5.

Phase 2B: Diel Tests During 1990 and 1991

DO vs. Time of Day Graphs for 1990 at I–1. Fig. 11a–h shows the DO vs. time of day graphs for the 8 diel testing dates between March and October 1990. The typical pattern observed during the summer of 1989 was dominant throughout these dates that cover the spring through fall months. One important change was that the morning minimum dipped below 5.0 mg/l in April in contrast to 1989 when that was not observed until June. Another difference from 1989 was that afternoon maxima did not reach as high as they had in May and August of 1989 when the readings went off the scale. The morning minima showed the same pattern as in 1989 with near zero readings occurring from July through October. This is evidently the time of year when conditions are most stressful in the slough. During these months DO was above 5.0 mg/l for about 10–12 hours per day.

SML–2. Fig. 12a–h displays the DO vs. time of day graphs at the SML–2 station for the March to October 1990 period. The unique characteristic of this station was evident during these months. On all but one date (September 24, 1990), DO increased after dark. The general pattern was for a small increase to occur by the early afternoon followed by a small decrease and then another increase in the early morning hours.

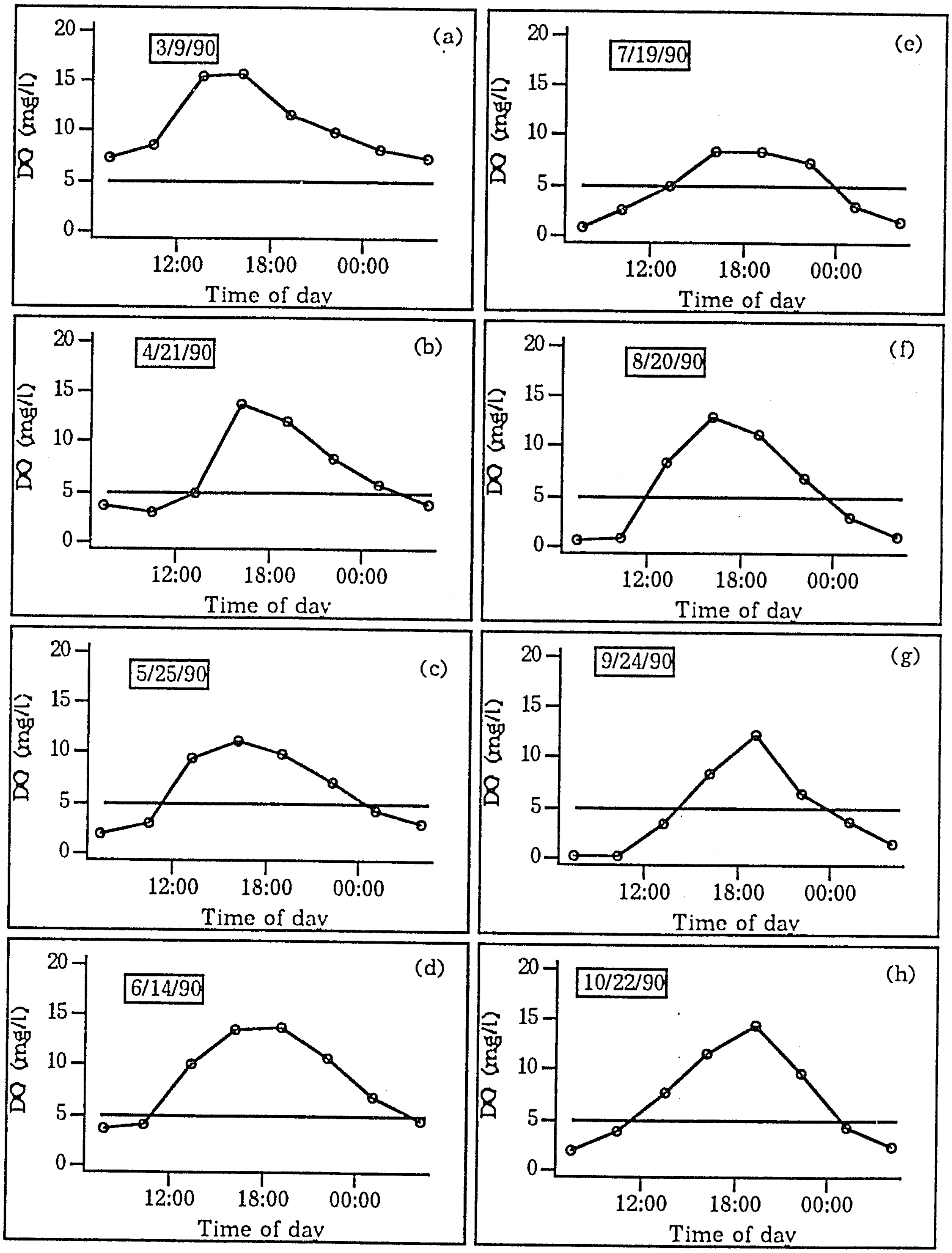

Fig. 11a-h. Charleston Slough pump (I-1) DO vs. time of day for 1990 phase 2B diel period of testing. Points are integrated averages of water column readings measured at 0.5 m intervals. Depth = 1.5 m. Horizontal line represents 5.0 mg/l standard.

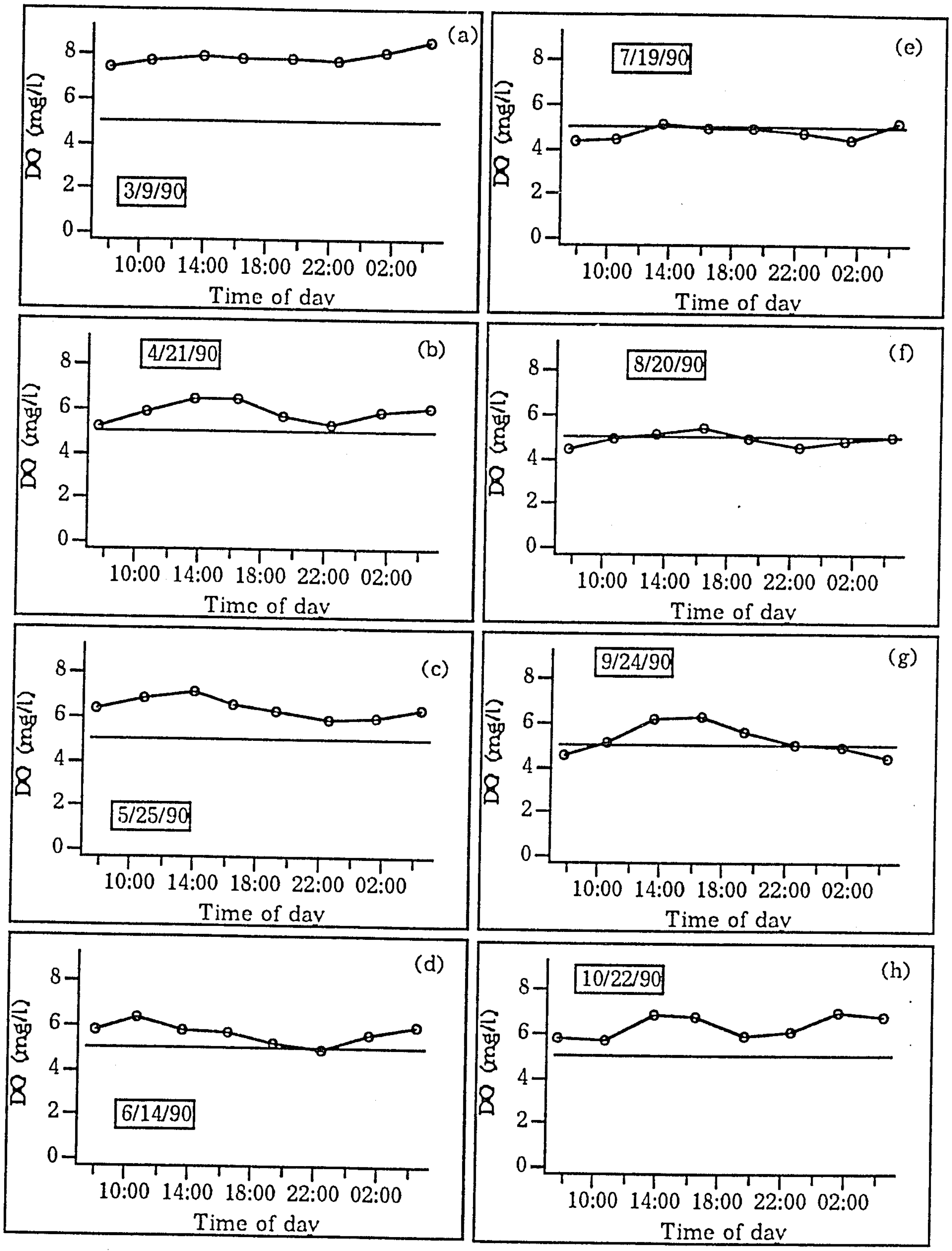

Fig. 12a-h. SML-2 DO vs. time of day for 1990 phase 2B diel period of testing. Points are integrated averages of water column readings measured at 0.5 m intervals. Depth = 3.1 m. Horizontal line represents 5.0 mg/l standard.

East end of lake. Fig 13a–h shows the DO vs. time of day graphs at E–1 and SML–1 for the 1990 testing dates. Both stations were not tested on the same date until September and October as shown on the graphs. At the east end of the lake there was, in general, a greater change from the minimum to the maximum reading for the day than at the SML–2 station, and the maximum tended to occur later in the day between 16:00 and 20:00 h. At both ends of the lake the lowest average DO values occurred during July and August. At SML–2 the average was below the lake standard during both of those months (Table 4).

Diel tests during 1991 when pump in normal operation. On May 22–23 and July 30–31, 1991 diel tests were completed with the same schedule and stations as for September and October 1990. On May 22–23, 1991 the DO pattern at the pump was similar to May 1990 (see Fig. 11c) with a morning minimum of 2.3 mg/l and an afternoon maximum at 12.7 mg/l. Average DO in the lake was higher than in May 1990 at both ends of the lake (Table 4). Fig. 14a–h shows the DO and temperature profiles at SML–1 for May 22–23, 1991 which are typical for this station during the summer months. The results are influenced by the fact that the SML–1 station is at the spot in the lake where water circulation is considered to be at a minimum (Rogge 1991).

The temperature pattern shows that the water column was almost isothermal at 8:05 h. Then as the day wore on, the surface waters heated up until the average water column temperature had increased 1.3 ºC by 17:00 h. At this time and the next the temperature was near isothermal down to 3 m and then dropped more than 1 ºC to the bottom at 4.3 m. During the summer in the late afternoon normally there are strong winds from the northwest, so this station

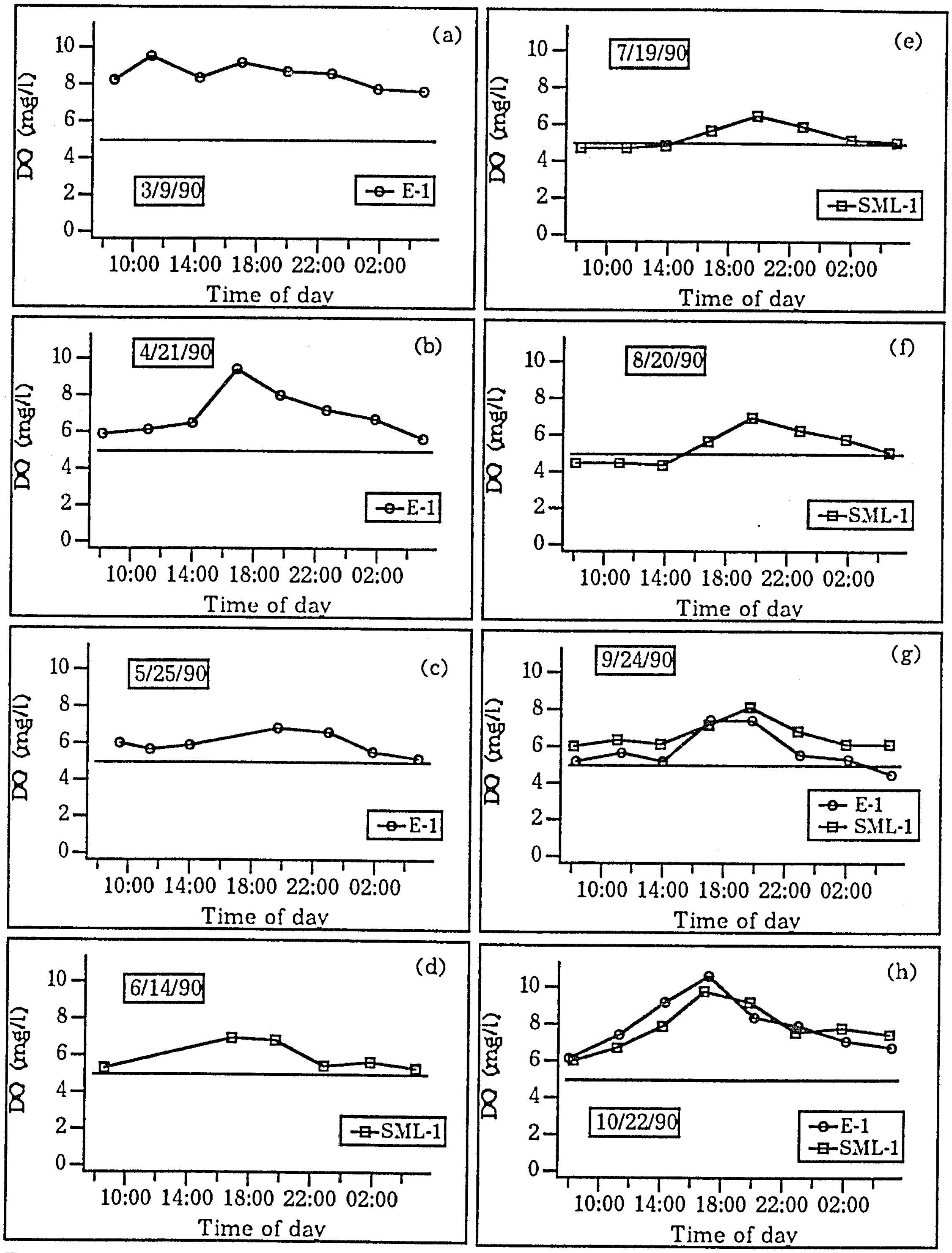

Fig. 13a-h. DO vs. time of day at east end of Sailing Lake for 1990 phase 2B diel period of testing. Points are integrated averages of water column readings measured at 0.5 m intervals. Depth = 4.3 m at SML-1. Depth = 0.9 m at E-1. Horizontal line represents 5.0 mg/l standard.

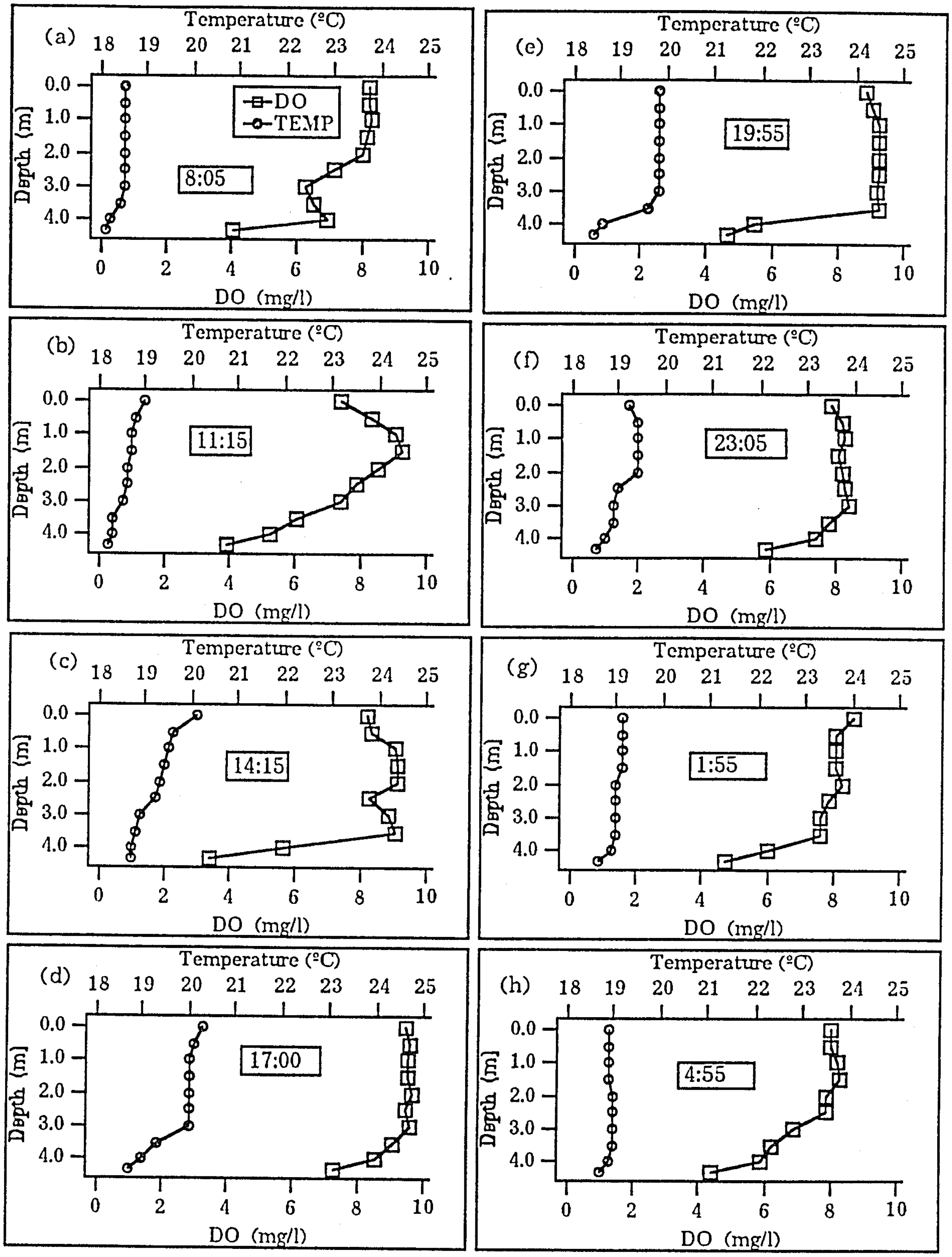

Fig. 14a-h. May 22-23, 91 SML-1 DO and temperature profiles.

at the east side of the lake has a greater fetch and is more affected by wind mixing than the west end of the lake. The temperature stratification did not last, however, as the water column became almost isothermal again during the late night hours showing the effect of the pumping schedule which prevents the lake from becoming permanently stratified.

For the DO profiles the distinguishing feature at this station is the larger dropoff near the bottom than at the SML–2 station. In general, the DO difference from top to bottom was greatest at this station. Another common occurrence shows up clearly at 11:15 h when the maximum DO in the water column was at a depth of 1 to 1.5 m depth rather than at the surface. This also occurred often in the late morning and early afternoon at SML–2. This phenomenon may be due to surface inhibition of photosynthesis. According to Fogg (1980, 30) the rate of photosynthesis at the surface is normally less than at some lower depth on sunny days mainly because the energy absorbed from visible light at the surface is greater than can be used by photosynthetic channels, so energy overflows into destructive photo-oxidation reactions.

Fig. 15 shows DO vs. time of day for all stations tested on July 30–31, 1991. The patterns were typical for this time of year, but it was extremely unusual that SML–1's maximum DO (8.3 mg/l) was higher than at I–1 (7.1 mg/l). This did not occur on any other date during the study, and the maximum DO at I–1 was the lowest for any date of testing. The July 1990 DO maximum (Fig. 11e) was the lowest of that year. During July of both years the heavy algal mats that covered the slough during the spring began dying off rapidly, so apparently oxygen demand was extremely high under these conditions.

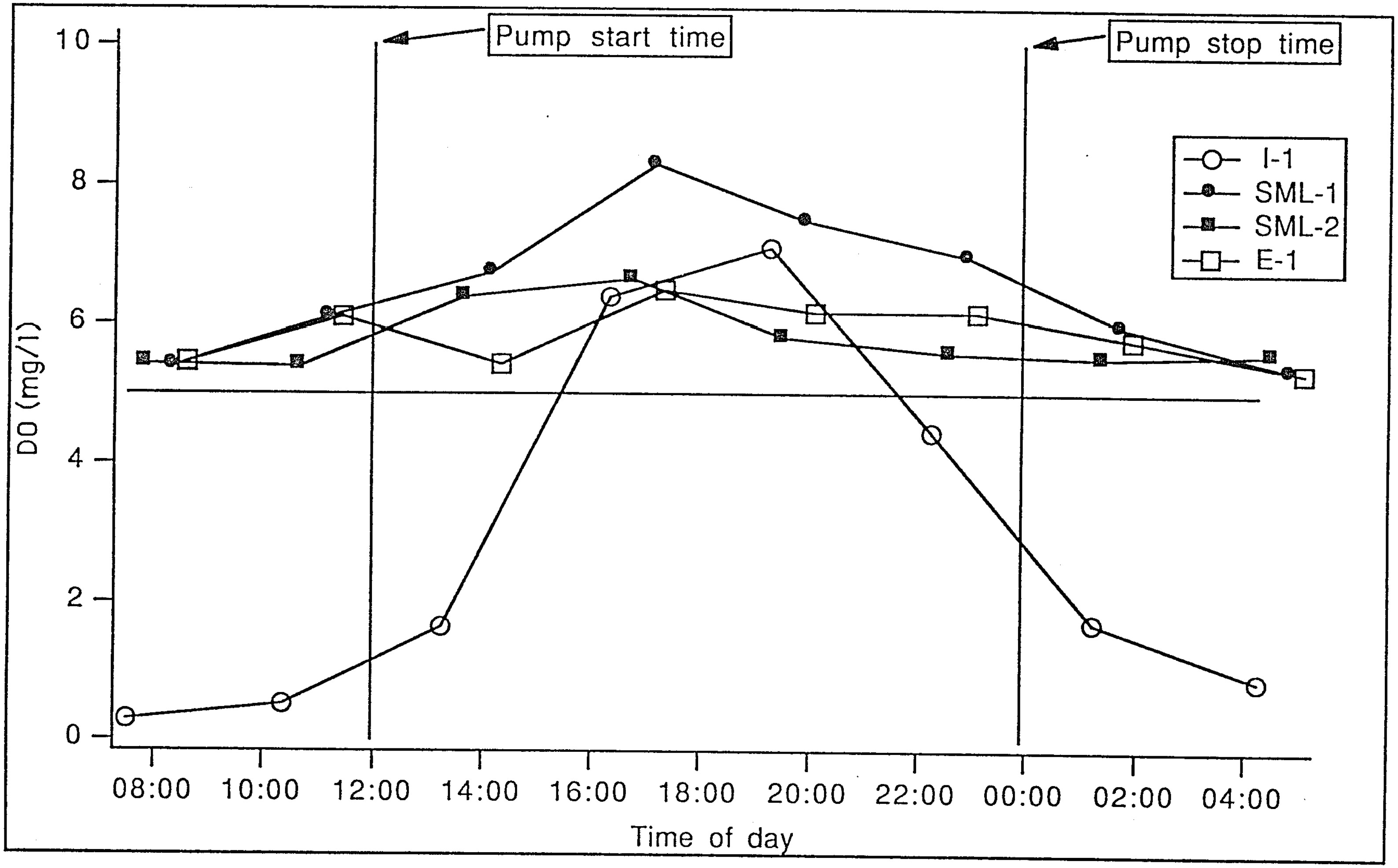

Fig. 15. July 30-31, 1991 DO vs. time of day at 3 stations in the Sailing Lake and at I-1 in Charleston Slough. Values are integrated averages of water column measurements taken at 0.5 m intervals from surface to near bottom.

Comparison of diel tests done with pump in operation and with pump shut down. On March 9–10, 1990 the pump was operating normally. From March 4 to March 13, 1991 the pump was removed for repairs. The weather conditions on these dates were very similar, so the data provide a chance to determine differences in the water column that can be attributed to the pump's operation.

Fig. 16a–h shows the DO and temperature profiles for March 9-10, 1990 at SML–2 station, and Fig. 17a–h shows the comparable profiles for March 8-9, 1991. Note that Fig. 16h is not at the same time as Fig. 17h. The pump was turned on at 11:15 h on March 9, 1990. In 1990 the profiles followed the typical pattern at SML–2. The water is isothermal in the morning. As the day goes on, the surface water heats up between 1–2 ºC, but by the evening the water returns to an isothermal condition at very nearly the same temperature as in the morning. This temperature pattern indicates that the lake can be considered totally mixed with essentially no thermocline. A 12 hour pumping schedule is obviously adequate to prevent the lake from becoming stratified during the summer months. The temperature increased near the surface by 1.2 ºC between 8:00 and 10:40 hours, but by 16:30 h the water column was nearly isothermal again. The DO typically showed little variation top to bottom. The maximum difference was 1.2 mg/l at 10:40 h shortly before the pump was turned on.

The 1991 results demonstrate the effect of the pump being off. For the first 2 readings the profiles are very similar to 1990. At 13:40 h, however, the temperature continued to heat up at the surface instead of beginning to cool

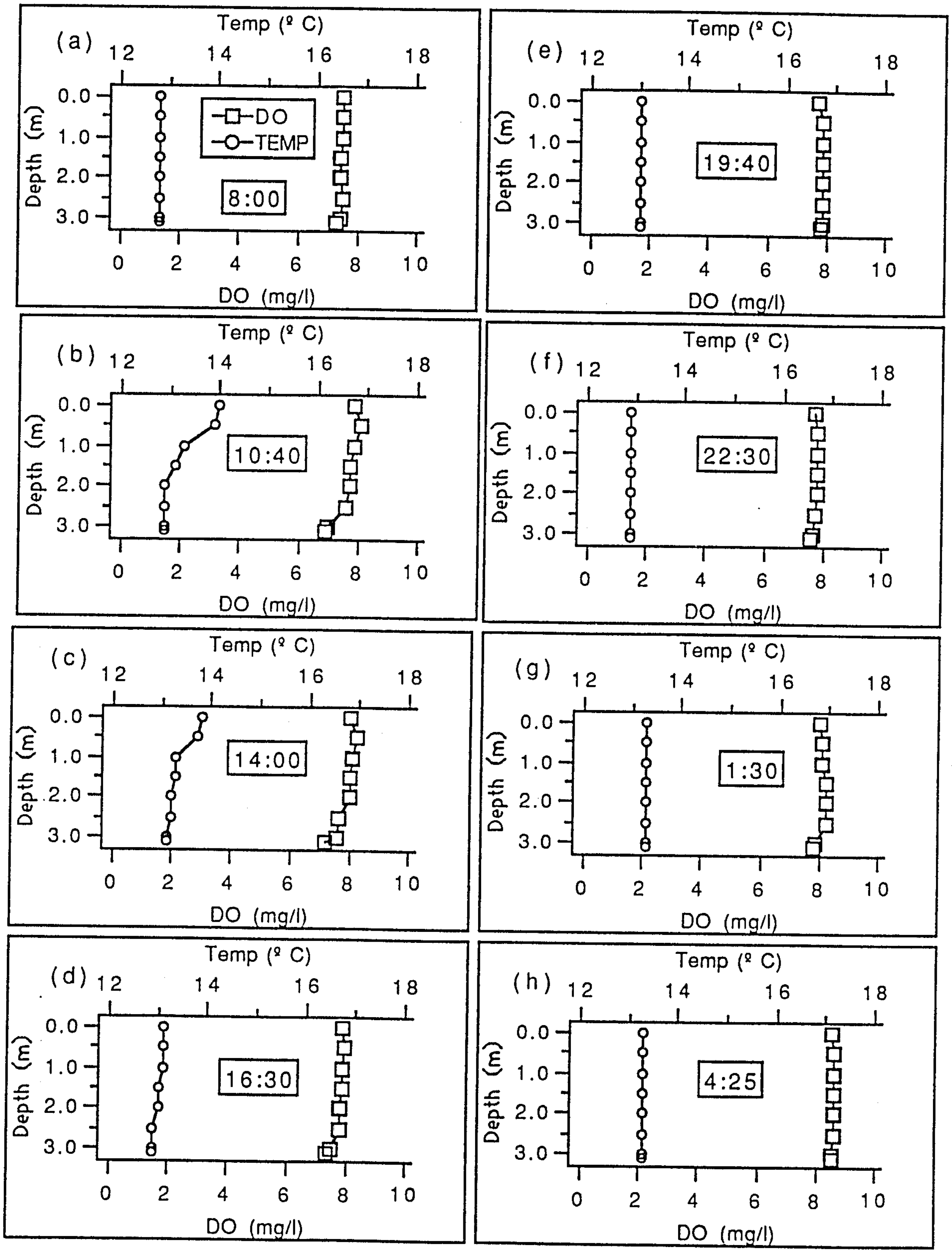

Fig. 16a-h. March 9-10, 90 SML-2 DO and temperature profiles.

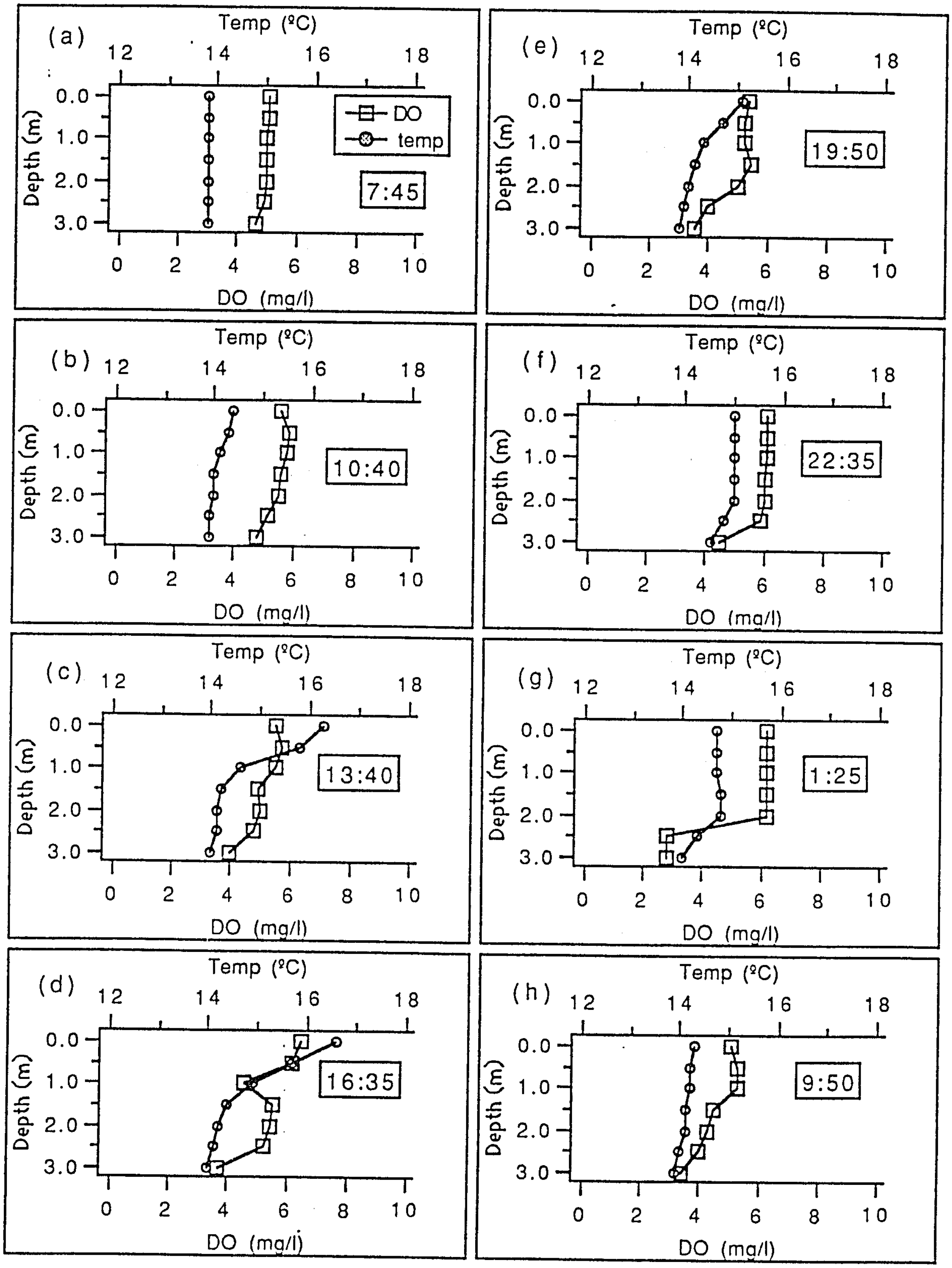

Fig. 17a-h. March 8-9, 91 SML-2 DO and temperature profiles. Charleston Slough pump was out of commission from March 4 to March 13.

already as in 1990. The temperature stratification between top and bottom at 13:40 and 16:35 h showed the maximum difference at this station for all dates tested (2.3 and 2.6 ºC, respectively). By 19:50 h the water column had begun to cool and destratify, but even by 1:25 h the temperature difference was still 0.7 ºC top to bottom. In 1990 the water column was isothermal for the last 4 readings. The 1991 DO profiles also showed the effect of the pump being off. Again at 13:40 h the difference from 1990 became evident. Instead of the difference between top and bottom decreasing as in 1990, it continued to increase. As the day went on, the bottom effect became more evident until at 1:25 h the difference between the 2.0 and 2.5 m readings was 3.3 mg/l. No similar differences were ever recorded at SML–2 when the pump was on. These results show that it is likely that the lake would become stratified and develop an anaerobic hypolimnion if the pump was out of commission during the summer months.

Fig. 18a–h shows the DO and temperature profiles at the pump for March 9–10, 1990, and Fig. 19a–h shows the comparable profiles for March 8–9, 91. The effect of the pump being off was much more extreme at the pump than it was in the lake. The 1990 profiles were typical for this time of year. At 10:20 h, before the pump was turned on, both the temperature and DO began to stratify, but at 13:40 h there was no stratification as the flow created by the pump had broken it down. This condition continued for the rest of the day.

In 1991 the profiles for the first 2 times are similar to the corresponding ones in 1990. By 13:20 h, without the pump on, extreme stratification had become established. The temperature difference was 6.2 ºC between 0 and

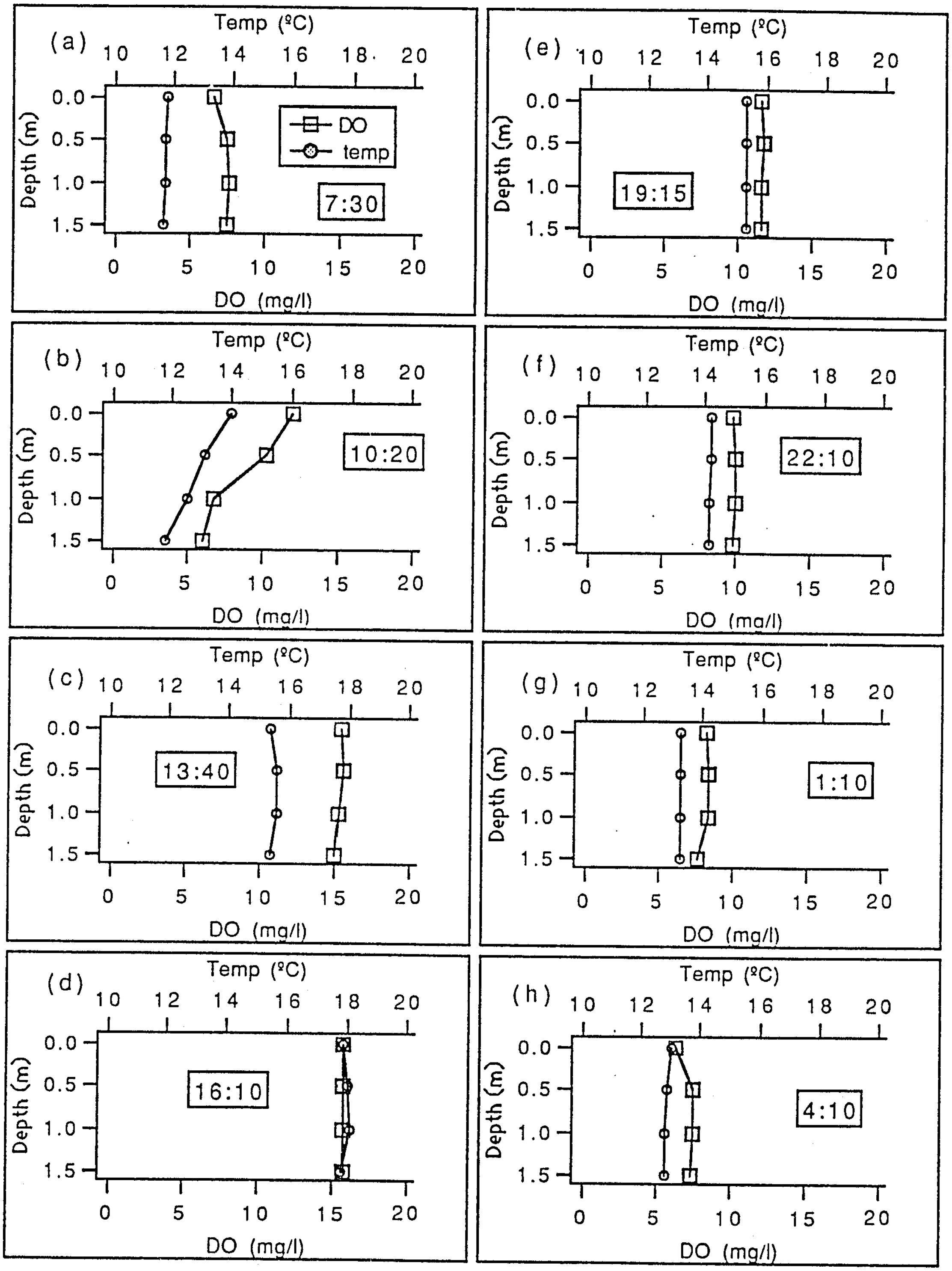

Fig. 18a-h. March 9-10, 90 Charleston Slough (I-1) DO and temperature profiles.

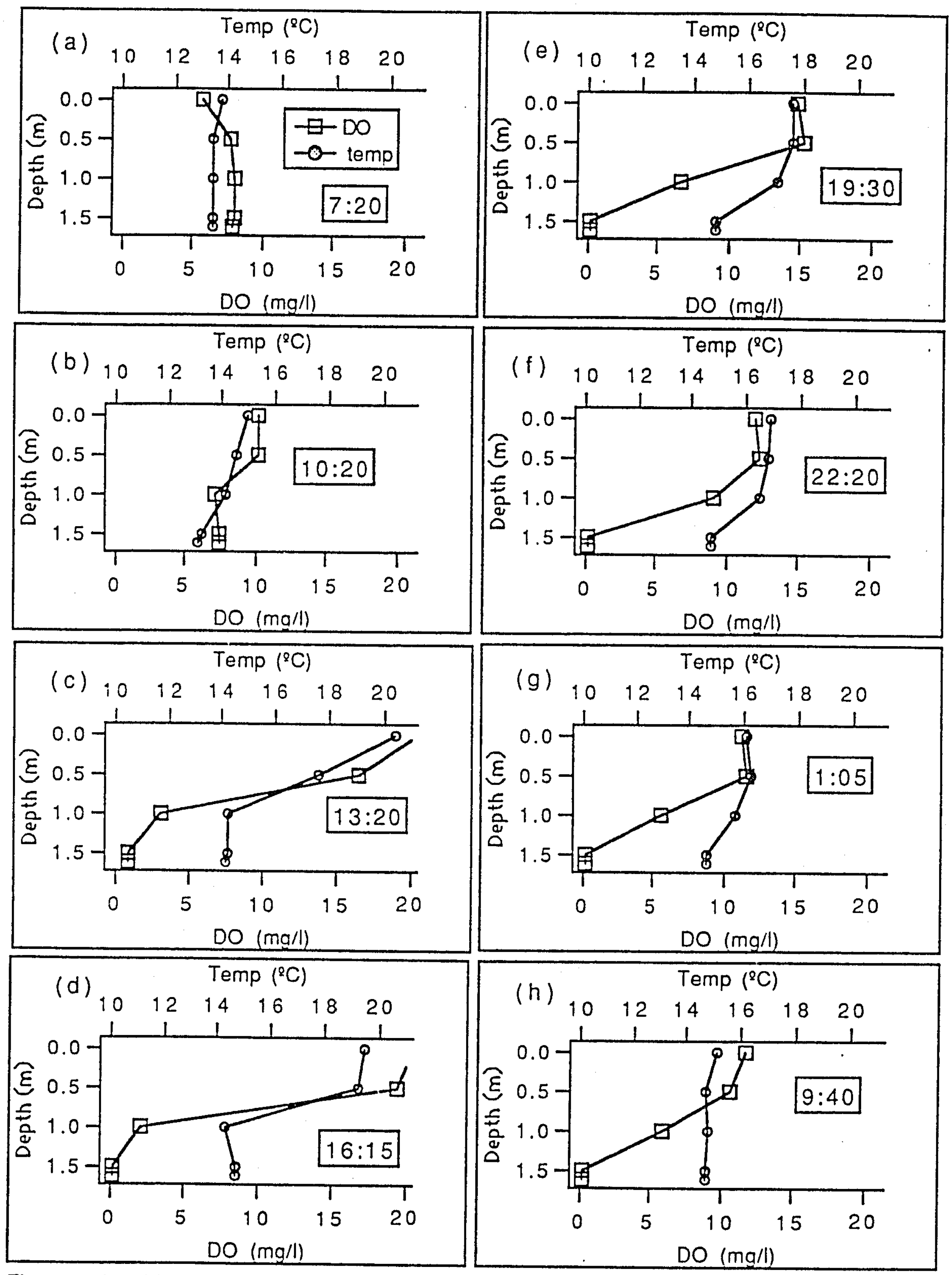

Fig. 19a-h. March 8-9, 91 Charleston Slough (I-1) DO and temperature profiles. Pump was out of commission from March 4 to March 13. Surface DO reading was off scale at 13:20 and 16:15.

1 m. DO was greater than 20 mg/l at the surface and near 0 mg/l at the bottom. The DO stratification did not break down until March 13 when the pump was turned back on. However, temperature stratification did break down as the surface water cooled back to the temperature of the bottom waters by the morning hours of March 9. When the thermocline became established, salinity readings were taken above and below it instead of the normal single reading. The salinity remained constant before 22:20 h, but at that time the reading above 1 m was 20.0 $^{o}/oo$ while below 1 m, it was 21.2 $^{o}/oo$. This condition also remained until the pump was turned back on. The water column had become stratified into 2 layers with a denser anaerobic layer trapped below the lighter aerobic layer.

Fig. 20a–e shows profiles that were taken over the next few days until the pump was turned back on March 13. Clearly there was no mixing between the layers of water during these days. The bottom waters remained at the same temperature and anaerobic until the pump was turned on again a few minutes before the readings taken at 11:10 h on March 13. Apparently salts continued to sink into the bottom layer as the salinity difference between the layers increased from March 9 to 13. On March 11 the salinity difference was 4.1 $^{o}/oo$. On March 12 it was 4.6 $^{o}/oo$, and on March 13, before the pump was turned on, it was 4.8 o/oo. At the 11:10 h reading on March 13, with the pump back on, the salinity was uniform throughout the water column (19.8 $^{o}/oo$) as usual with the pump on.

The episode of the pump being off for several days occurred at a time of year when winter conditions were still prevailing. The fact that significant differences in stratification of temperature, DO, and salinity began to occur

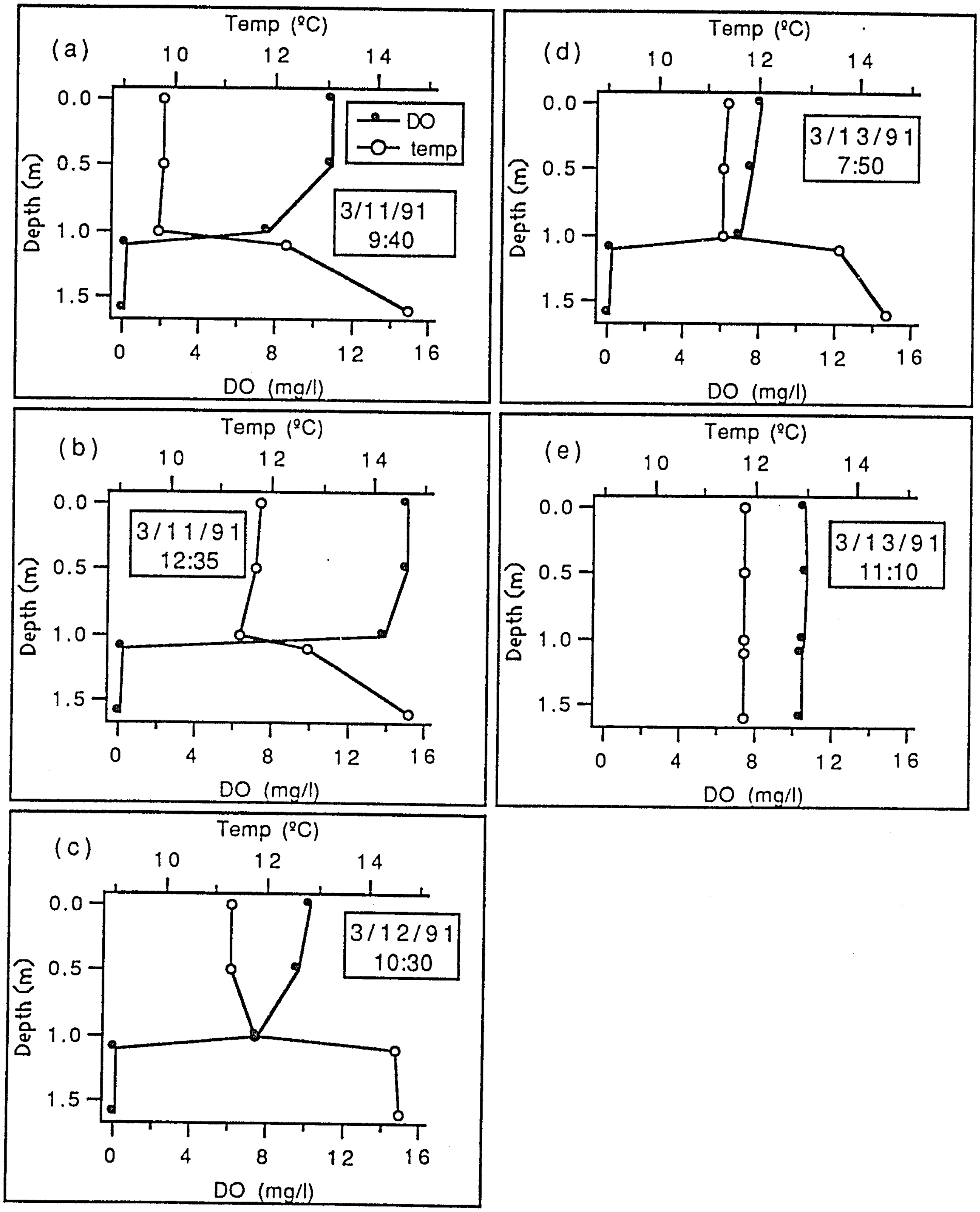

Fig. 20a-e. DO and temperature profiles at Charleston Slough (I-1) on dates when pump was out of order under these conditions indicate that under summer conditions the lake would most likely develop a thermocline and an anaerobic hypolimnion on the bottom of the lake if the pump were to go out of order.

Significant Differences Between the Stations

Table 5 summarizes results of the diel testing for temperature and DO changes at I–1 and at the 3 stations in the lake. Table 6 shows the results of paired difference one-tailed t-tests comparing the results shown in Table 5 for the lake stations. Comparing these parameters in the slough and the lake, it is clear that the water undergoes some significant changes when it enters the lake. Also there are some small but consistent differences between the stations in the lake.

Min-max Δ temp ave. The temperature change from the minimum average round to the maximum average round of the water column readings at I–1 was always greater than at any of the stations in the lake for any particular day of testing regardless of the season. These results reflect the fact that the volume of the lake is about 5 times the volume of the slough, and the slough is much shallower than the lake (slough is less than 1 meter except near the pump while lake is only shallow very near the shore). Light penetrates to the bottom of the slough and thus heats the entire water column as well as the bottom. In the lake this only occurs near the shoreline. E–1, the lake outlet which has a depth from 0.9-1 m, has the largest value of the 3 lake stations.

Top-bottom max. Δ temp ave. The results for the maximum temperature difference from top to bottom in the water column for any round of testing on a

Table 5.--Summary of Temperature and DO Changes at Charleston Slough (I-1) and 3 Stations in the Sailing Lake

Station	N	Min-max Δ temp. ave.	Min-max Δ temp. range	top-bottom max. Δ temp. ave.	top-bottom max. Δ temp. range
I-1	23	4.0	0.4-6.5	0.8	0.2-2.7
SML-2	19	0.5	0.2-1.4	0.7	0.1-1.5
SML-1	10	0.8	0.3-1.3	1.0	0.5-1.8
E-1	15	1.3	0.2-2.1	0.4	0.0-0.9
		Min-max ΔDO ave.	Min-max ΔDO range	top-bottom max. ΔDO ave.	top-bottom max. ΔDO range
I-1	23	10.0	4.4-16.1	*	*
SML-2	19	0.7	0.1-2.1	1.7	0.3-4.1
SML-1	10	2.0	0.3-3.8	3.5	0.9-5.9
E-1	15	2.1	0.1-5.2	0.5	0.1-1.1

Notes: Min-max Δ temp. and min-max ΔDO represent the change in the parameter from the average of the water column readings of the lowest morning round to the average for the highest round for the day.

Top-bottom max Δ temp and top-bottom max ΔDO represent the maximum change from top to bottom for any round of testing on a particular date.

*Top-bottom max. ΔDO is omitted for I-1 because the maximum DO values were not consistently at the top of the water column, and minimum values were not consistently at the bottom of the water column.

Table 6.--Paired Difference One-tailed t-tests of Parameters Shown in Table 5 Comparing Lake Stations

Stations	Parameters	t Values	Prob.	DF
SML-1 vs. SML-2	Min-max Δ temp.	2.861	0.021	8
	Top-bottom max. Δ temp.	3.327	0.010	8
	Min-max Δ DO	4.848	0.001	8
	Top-bottom max. Δ DO	2.844	0.022	8
SML-1 vs. E-1	Min-max Δ temp.	4.159	0.025	3
	Top-bottom max. Δ temp.	7.034	0.006	3
	Min-max Δ DO	0.971	0.403*	3
	Top-bottom max. Δ DO	2.467	0.002	3
SML-2 vs. E-1	Min-max Δ temp.	5.2	0.000	12
	Top-bottom max. Δ temp.	4.384	0.001	12
	Min-max Δ DO	3.792	0.003	12
	Top-bottom max. Δ DO	4.308	0.001	12

*The min-max Δ DO comparison between SML–1 and E–1 is the only one of all these tests that shows no significant difference between the stations particular date show the effect of the daily pumping schedule. The pumping destroys the thermocline that starts to form in the slough as discussed previously and prevents a thermocline from forming in the lake so that there is no large change in temperature from top to bottom at any of the stations in the lake. Pastorok, Ginn, and Lorenzen (1981, 7) surveyed studies of the effects of artificial circulation and found that the temperature of upper waters decreased a few degrees from what it would have been without artificial circulation, while the temperature of deeper waters increased as much as 15–20 ºC.

Min-max ΔDO ave. The average DO increase in the slough from the minimum average to the maximum average of the water column readings is very large compared to the lake change at any station. Within the lake, DO changes more at the east end of the lake than at the west end. These results varied directly with the min-max Δ temp. results cited above. The greater the temperature increase during the day at a station was, the greater the DO change at the same station. However, although there was a significant difference (prob. = 0.025) between the min-max Δ temp.for SML–1 vs. E–1, there was no significant difference between SML–1 and E–1 for min-max ΔDO.

Top-bottom max. ΔDO ave. This parameter represents the average maximum change in DO from top to bottom for any round of testing on a particular date. It was not calculated at I–1 because DO was not always highest near the top of the water column or lowest on the bottom. This can be attributed to the pumping action keeping the water column well-mixed. In the lake the values vary consistently according to the depth of the station. The greater the depth, the greater the change in DO from top to bottom.

Some Conclusions Based on Phase 2 Results

Charleston Slough. The testing done at the pump during phase 2 reinforced the conclusions drawn from the phase 1 results. The slough's diel DO patterns are mainly influenced by the heavy algal blooms which occur seasonally as well as the seasonal variations in the temperature of the water.

From spring to fall the daily DO pattern is sinusoidal. The morning minimum DO decreases as the temperature increases in the spring. By July the minimum is near 0 mg/l. The minimum does not begin to increase until the temperatures begin to decrease in late fall.

During the winter months of December and January, the DO pattern shows a more complex pattern with a much slower rate of change per day than during the rest of the year. Extremely high DO readings still occur because of microalgal blooms, but DO does not ever drop below the 5.0 mg/l standard. The much lower rate of plant respiration and decomposition during the colder months would account for the much higher minimum DO values. Boyd (1979, 27) stated that a 10 ºC increase in water temperature often doubles the rate of decomposition. The difference in the average temperature at I-1 dropped by more that 10 ºC from the summer maximum over 23 ºC to the winter minimum below 10 ºC (Table 4).

The summer and fall seasons are the times of most concern with regard to low DO in the slough. If the pump was turned on from 7:00-19:00 h during these seasons, water with extremely low DO would be pumped to the lake for several hours during the morning. Boyd (1979, 43) discusses the effects of mixing anaerobic water layers with aerobic layers. The immediate oxygen demand exerted on the aerobic water is greater than would be expected from dilution alone because of the presence of reduced substances (such as H_2S) in the anaerobic water which consume oxygen by a process called chemical oxygen demand (COD).

Sailing Lake. The diel DO patterns at the lake stations were considerably more complex than at the pump. There are more factors at work in the lake than in the slough. The morphometry of the lake, the currents in the lake set in motion by the pumping action, and the photosynthesis and respiration cycles in the lake itself are important factors along with the quality of the water that is pumped to the lake in determining the diel cycles that occur.

Diel changes in the deeper lake are significantly slower than at the shallow pump station. The daily range of values of temperature and DO in the lake is significantly less than in the slough regardless of the season.

However, the results also show that the average DO in the lake can change rather quickly dropping from an above standard condition to well below the standard within a few days as occurred at the end of August 1989 when the average lake DO dropped from 6.5 mg/l to 4.2 mg/l in 4 days.

The mixing of the lake waters by the pumping action prevents temperature stratification from occurring in the lake during the summer months, keeping the temperature profile almost constant from top to bottom. As a result DO stratification is also much less than it would be without the pumping action.

Though the differences among the lake stations are small, they are consistent and statistically significant as shown by the results in Tables 5 and 6. The deeper, less well circulated water at SML–1 shows the greatest top to bottom variation in temperature and DO. The shallow, well-mixed water at E–1 shows the greatest variation in temperature and DO from morning minimum to afternoon maximum, but the smallest top to bottom changes. The SML–2 station which is closest to the turbulence created by the plume from the pumped water entering from the bottom of the lake shows the smallest variation in the changes in DO and temperature during the course of a day. Without the pumping action, the differences between the stations would probably become much more pronounced as lake waters would be less well-mixed, and local conditions at each station would become more dominant.

Results of Phase 3 Weekly Testing During 1990 and 1991

Table 7 shows the seasonal averages for water quality parameters at G-1 and I–1 in Charleston Slough and all stations in the Sailing Lake computed from the weekly testing results. In the slough the seasonal differences are generally greater than in the lake except for temperature which shows a seasonal difference between 9 and 11 ºC regardless of the station. More analysis of the results from this table is included in the discussion below on the different stations and parameters.

Charleston Slough

G-1 DO readings compared to afternoon I-1 readings. Fig. 21 shows the DO readings measured at the outside of the gate (G-1) at times when water was entering the inner slough from April 1990 to December 1991 as well as the DO readings at I-1 in the early afternoon when the pump was operating from August 1990 to December 1991. During the time from August 1990 when both stations were tested, most of the G-1 readings were done in the early afternoon either

Table 7.--Seasonal Averages of Weekly Data at Charleston Slough (G-1 and I-1) and 3 Stations in Sailing Lake for 1990-91

Station	Season	# of dates tested	Ave. DO (mg/l)	Ave. Temp. (ºC)	Ave. Sal. (°/oo)	Ave. Secchi depth (m)
G-1	winter	11	8.8	10.5	24.6	0.4
G-1	summer	25	7.1	21.4	24.9	0.2
I-1 (P.M.)	winter	26	9.5	11.9	24.5	n. d.
I-1 (P.M.)	summer	40	5.4	21.2	27.2	n. d.
I-1 (A.M.)	winter	36	6.2	10.6	23.3	0.5
I-1 (A.M.)	summer	57	1.7	19.5	25.8	1.0
I-1 (A.M.) (P.M. dates)	winter	26	5.9	10.3	24.5	0.5
I-1 (A.M.) (P.M. dates)	summer	40	1.6	19.4	27.0	1.0
SML-1	winter	36	7.1	12.2	25.2	1.3
SML-1	summer	57	5.8	21.2	25.7	1.2
SML-2	winter	36	6.9	12.1	25.1	1.5
SML-2	summer	57	5.9	21.0	25.7	1.3
E-1	winter	36	7.5	12.4	25.1	1.6
E-1	summer	57	6.2	21.3	25.7	1.4

Notes: A.M. indicates morning when pump is off. P.M. indicates early afternoon when pump is on. Winter is November to March. Summer is April to October. n. d. means no data were collected at that time.

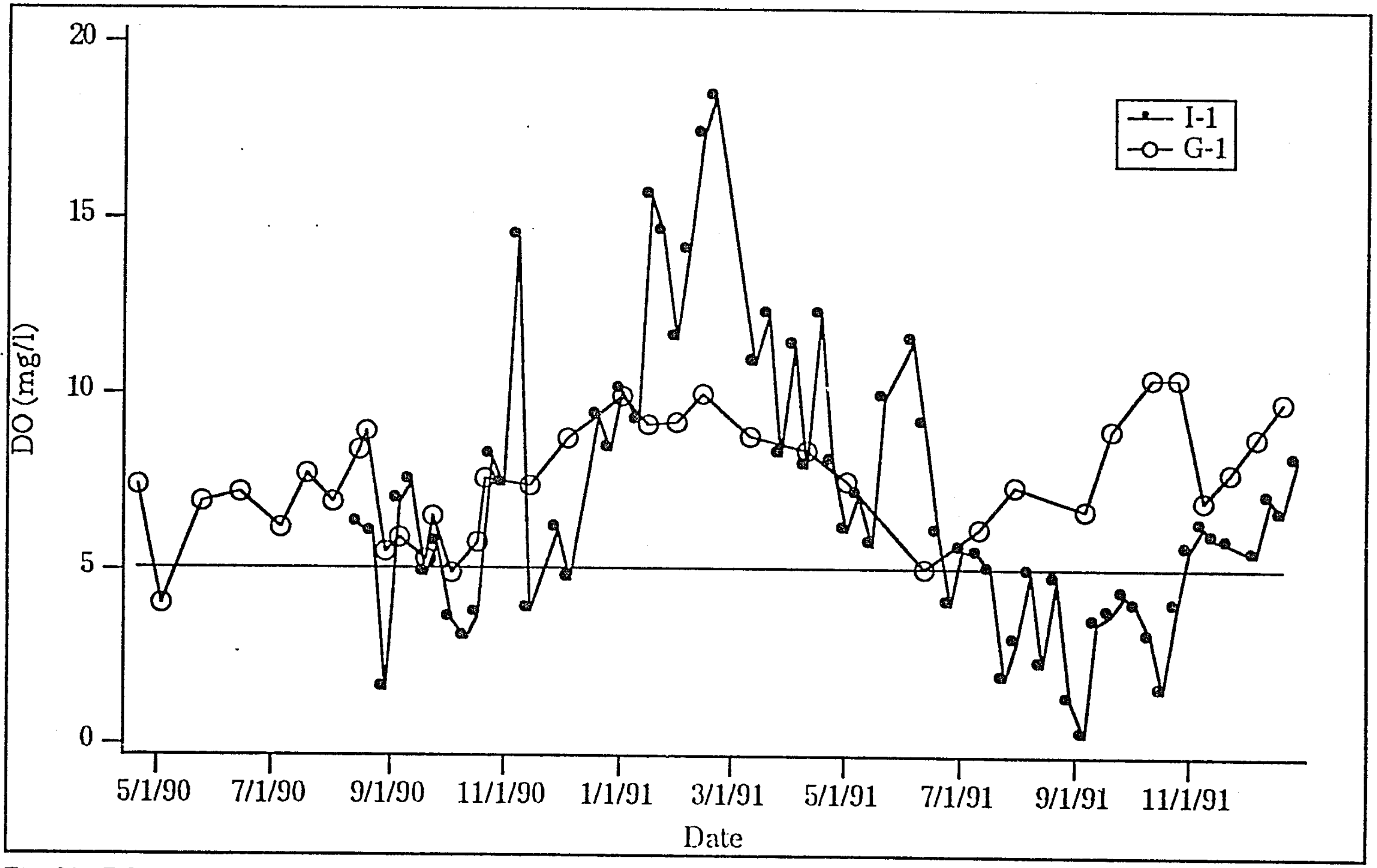

Fig. 21. DO at Charleston Slough (G-1 and I-1). G-1 readings were taken near high tide when water was flowing into the slough usually in the early afternoon. I-1 readings were taken in the early afternoon when the pump was on. Values are average of water column readings at 0.5 m intervals.

shortly before or after the I-1 readings depending on the timing of high tides, so the readings give a fair comparison of the changes to the water as it passes through the inner slough from the gate to the pump. Comparing the time period when both stations were tested, the variance at I-1 (15.2) was significantly greater ($\alpha = 0.01$) than the variance at G-1 (2.8). Just as the daily DO variation increased greatly as water entered the inner slough through the gate (see phase 1 results section above), so also did the seasonal DO variation increase significantly. The difference between the average DO in summer and winter at G-1 was 1.7 mg/l while the difference at I-1 was 4.1 mg/l (Table 7). From July to November 1991 the I-1 readings were consistently below 5.0 mg/l while the G-1 readings were never below 5.0 mg/l. This result shows that there is no evidence to support the hypothesis that low DO readings in the slough result from low DO in the incoming bay water which was included as one of the possible reasons for the 1988 decline in the monthly DO readings in the DEIR on the Charleston Slough restoration project (BCDC 1990) The DO data collected at the PA C-R testing station (shown on Fig. 2) from 1981 to 1989 by SBDA and PARWQCP shows that there was no time period during the 1980's when bay waters in the vicinity were below standard levels for a long time period. The average of the data set is 8.0 mg/l (N=184), and there were only 2 readings below the 5.0 mg/l standard during the entire testing period (Stevenson et al. 1987; PARWQCP 1987-1989).

<u>I-1 morning DO and temperature readings</u>. Fig. 22 shows the results for DO and temperature of the weekly tests at the Charleston Slough pump which were taken in the morning before the pump was turned on. The seasonal

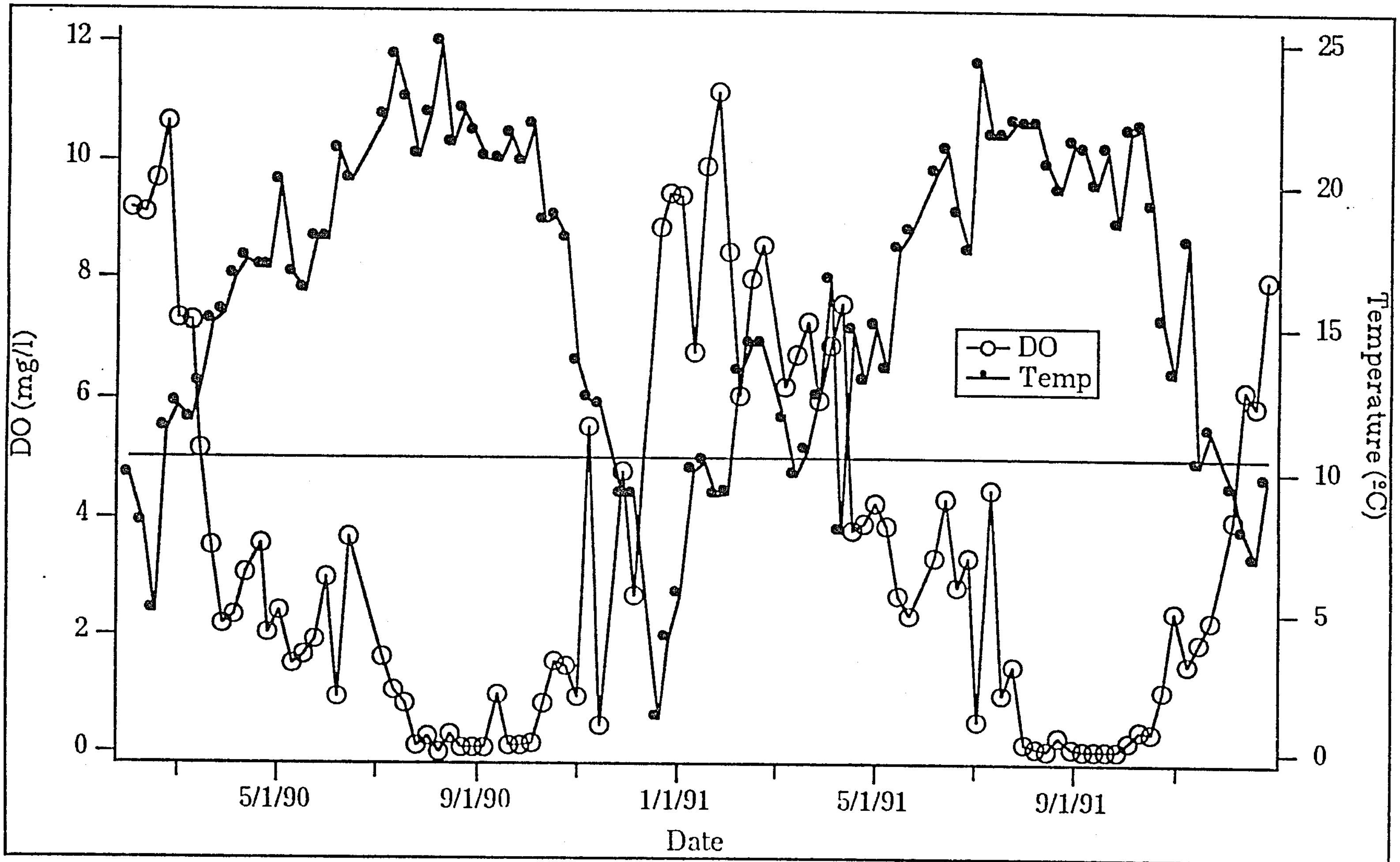

Fig. 22. Weekly morning DO and temperature readings at Charleston Slough (I-1). Values are average of water column readings taken at 0.5 m intervals from surface to near bottom. Depth = 1.5 m. Horizontal line at 5.0 mg/l represents lake DO standard.

pattern of low DO readings on summer mornings that was first observed during the Phase 1 1989 tests previously described continued in both 1990 and 1991. In 1990 the DO dropped below 5.0 mg/l on March 22 and there were no readings above 5.0 until November. Then from December 21, 1990 until April 11, 1991 DO was always above 5.0. From April 18, 1991 until December 6, 1991 DO was again below 5.0 each week. In both years DO was near 0 mg/l from July through October. Table 7 shows that the average summer DO was 4.5 mg/l less than the average winter DO.

Fig. 22 shows an inverse relationship between temperature and DO. In both years the DO dropped below 5.0 mg/l when the temperature reached about 15.0 ºC and didn't stay above 5.0 mg/l in the fall until the temperature had dropped below 8.0 ºC. The Pearson product moment correlation coefficient for temperature versus DO was –0.81.

The average increase in DO from morning to afternoon at I-1 was similar in both the winter and summer (3.6 mg/l in winter and 3.8 mg/l in summer). Temperature increased an average of 1.6 ºC during winter and 1.8 ºC during summer from morning to afternoon. The average difference in salinity from morning to afternoon was insignificant (Table 7).

<u>Sailing Lake</u>

<u>DO</u>. Fig. 23a–c shows the results of the weekly testing at the 3 stations in the Sailing Lake for DO during 1990–91. All readings were taken during the morning. All stations showed a similar pattern over the course of these 2 years, generally going up or down from week to week together. In Table 7 the seasonal averages show that the difference between the summer and winter

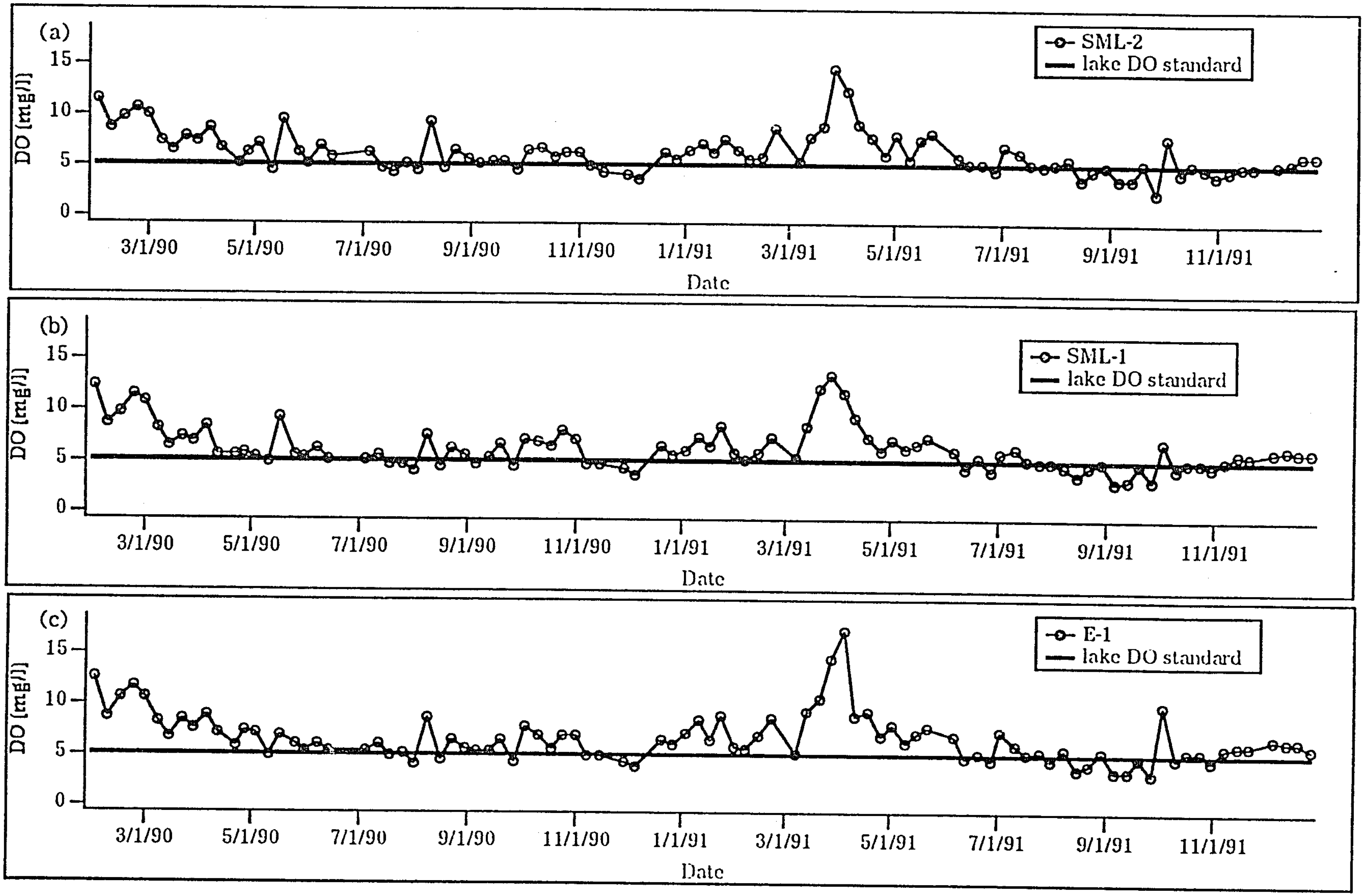

Fig. 23a-c. Weekly morning DO readings at 3 stations in the Sailing Lake. Values are the average of water column readings measured at 0.5 m intervals from surface to near bottom. SML-2 depth = 3.1 m. SML-1 depth = 4.3 m. E-1 depth = 0.9 m.

DO was about the same for all stations (average difference for all stations equalled 1.2 mg/l). However, this seasonal difference was much less than the seasonal difference for the morning slough readings (4.5 mg/l).

The highest values for all stations occurred on April 4, 1991 when there was an algal bloom in the lake. From August to October 1991 DO was below the 5.0 standard for the lake most of the dates of testing. During those months the afternoon DO at the pump was also below 5.0 for the most extended period of time during both years of testing.

Temperature and salinity. Fig. 24a–b shows the weekly results for temperature and salinity for the 3 stations in the Sailing Lake. The sudden jump in salinity occurred after the meter was cleaned for the first time. Apparently the salinity values during the summer of 1990 would have been higher at an earlier date if the meter had been serviced earlier. The difference in salinity from winter to summer was much less in the lake than it was in the slough. The average seasonal difference for all stations in the lake was 0.6 $^{o}/oo$ but 2.5 $^{o}/oo$ in the slough.

There was little variation in these parameters between the stations on each date. The results in Table 7 for temperature and salinity at these stations confirm the small differences among the lake stations. These small differences correspond with the diel results discussed earlier and demonstrates how well-mixed the lake is under the 12 hour pumping schedule.

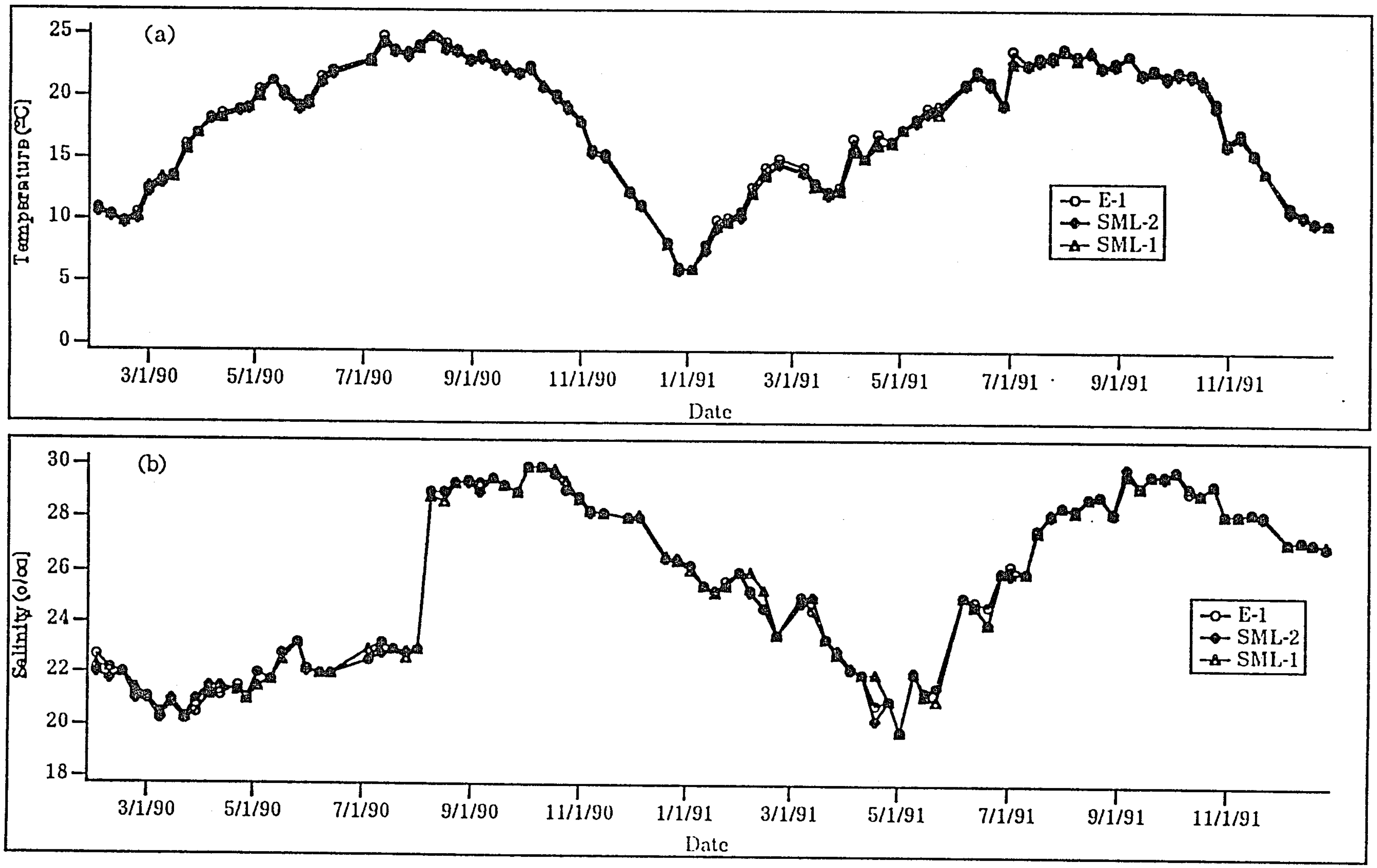

Fig. 24a-b. Weekly (a) temperature and (b) salinity readings at 3 stations in the Sailing Lake. Temperature values are average of water column readings made at 0.5 m intervals from surface to near bottom. Salinity values are readings at about 1 m depth.

Comparison of pH Throughout the System

Fig. 25 shows the results of the pH readings at G-1, I-1, and SML-2 during 1990 and 1991. The readings at SML–2 were representative of all stations in the lake as there was never more than a 0.1 difference in the pH readings on any date. During 1990 a definite pattern of change in pH was established as water passed through the system. Between G-1 and I-1 pH increased up to 1.1 units and then decreased up to 0.7 units at SML–2. This can be explained by the greater photosynthetic activity which occurs in the inner slough. As Goldman and Horne (1983, 98) explain, pH increases when DO increases and CO_2 decreases, due to increased photosynthetic activity. The maximum pH occurred at SML–2 in April 1991 when an algal bloom was occurring in the lake.

Comparison of Secchi Depth Throughout the System

Fig. 26 shows the secchi readings at G–1, I–1, and SML–2 during 1990 and 1991. Secchi depth at G-1 varied much less than at either of the other 2 stations and was almost always considerably lower as well. Inner Charleston Slough acts as a settling pond for the turbid water entering from the bay. In this regard Charleston Slough is what Jurgen (1981, 154) refers to as a pre-reservoir. These have been traditionally used in Germany to trap sediments upstream from reservoirs to slow down the rate of siltation in the reservoirs. Research has shown that pre-reservoirs also can act as nutrient traps eliminating significant amounts of phosphates from the water column depending on the residence time of the water in the pre-reservoir (Jurgen 1981, 154).

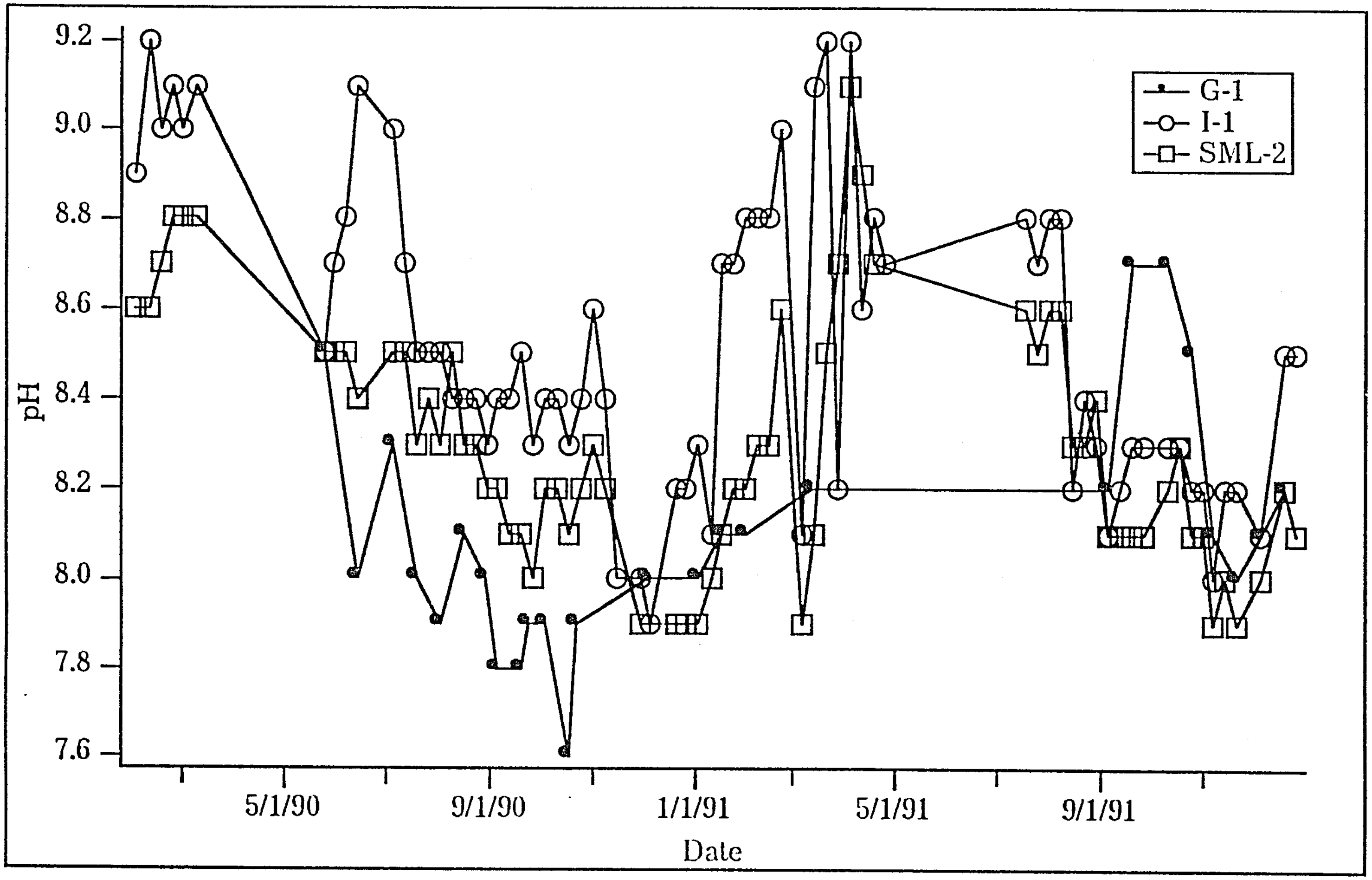

Fig. 25. The pH at Charleston Slough (G-1 and I-1) and at SML-2 in the Sailing Lake. Readings were taken near surface.

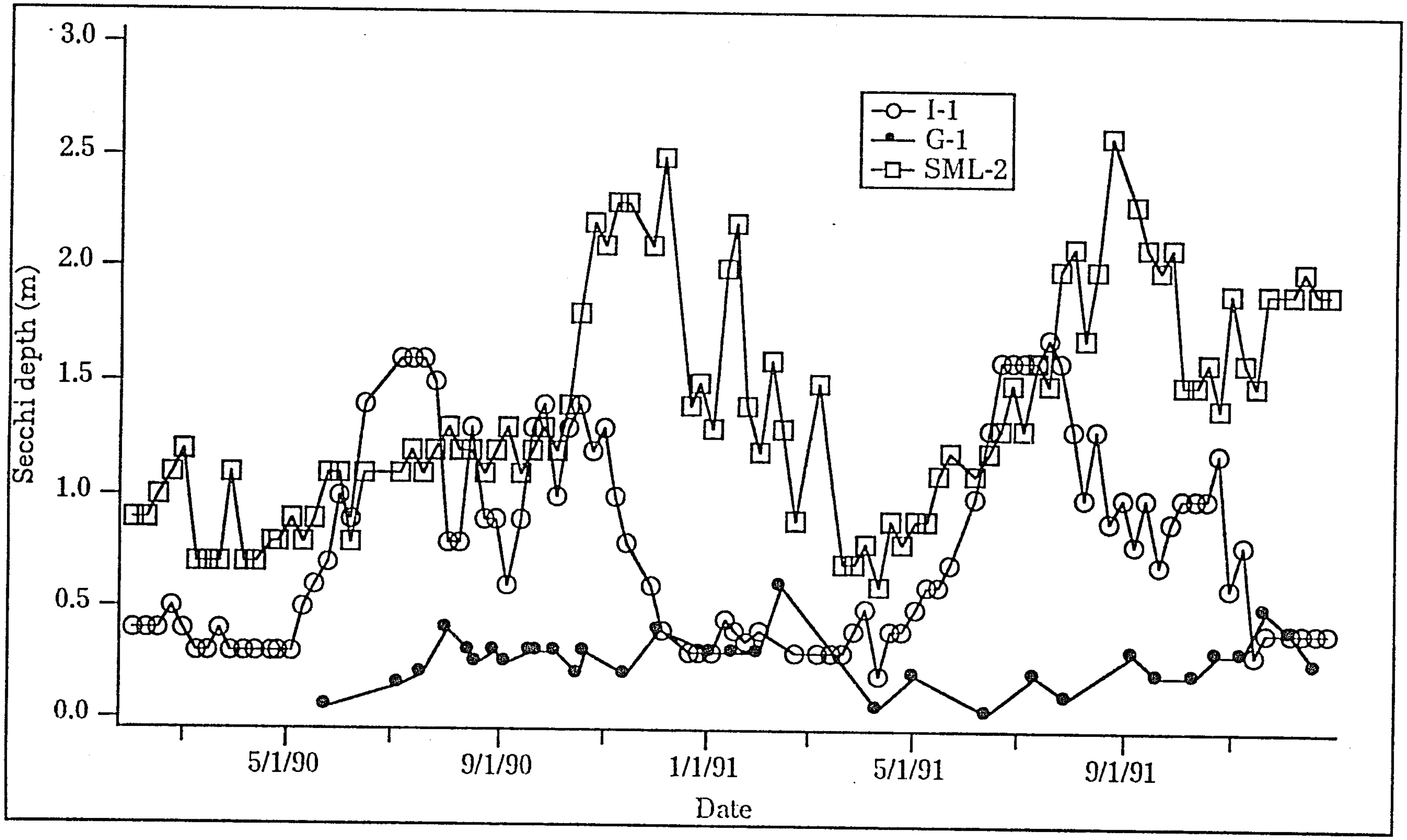

Fig. 26. Secchi depth at Charleston Slough (G-1 and I-1) and SML-2 in the Sailing Lake.

At I-1 Secchi depth showed the effect of the cycles of algal growth and decay. In the winter months Secchi depth was lower (average = 0.5 m) when microalgae were dominant. As the macroalgal mats increased during the spring and early summer, the Secchi depth also increased. The maximum readings occurred during June and July in both 1990 and 1991 (summer average = 1.0 m). Then as the algal mats decayed and disappeared during the late summer and fall, the Secchi depth decreased again. This trend was similar to that found by Lonzarich (1989, 31–36) in his study of the Leslie Salt Company ponds near Alviso in South San Francisco Bay. He took Secchi depth readings from March to September in 1986. For Pond A9, the one most similar to Charleston Slough, the Secchi depth started at 1 m, increased to 3 m in May and then decreased to about 0.4 m in September. The A9 pond showed a similar algal growth and decay pattern as occurred at Charleston Slough. Goldman and Horne (1983, 390) point out that when algae is in clumps, Secchi depth readings will be higher than expected based on the amount of chlorophyll present, and that under such conditions Secchi readings underestimate nuisance algal conditions.

At SML–2, representative of the lake stations, the Secchi depth is generally greater than in the slough expect when the I-1 readings reached their yearly maximum during June and July.

Some Conclusions from Phase 3 Results

The results of phase 3 are consistent with the other 2 phases of the study. There is additional evidence that the conditions in the slough greatly increase the seasonal variability in DO values over what occurs in the incoming bay waters as shown by the differences between the G–1 DO data and the afternoon I–1 DO data. During the summer the high rates of respiration and decomposition use up virtually all the oxygen that is being produced by photosynthesis on a daily basis. During winter when the rates of respiration and decomposition are much lower, oxygen levels are higher in the slough than anywhere else in the system because photosynthesis still occurs at a high rate.

As with the phase 2 results, the phase 3 results show that the lake's DO pattern shows less extreme variability than the slough water. However, the lake DO can fluctuate considerably from week to week in response to its own cycles of algal bloom and decay. The pumping action prevents the lake's DO from dropping to the extremely low values observed at the slough, but it does not prevent DO in the lake from dropping below the lake standard especially during the late summer and fall period.

The July-October period is clearly the time of greatest concern in both the slough and the lake. The average of the morning I–1 readings during those months in 1990 and 1991 was 0.58 mg/l (N = 34). On most mornings during these months the slough waters are anaerobic, and the slough is an inhospitable environment for most organisms. Aesthetically, it is also unpleasant for Shoreline visitors because they have to view piles of decaying algae and endure the strong odors from the H_2S that is being produced under these conditions.

The average of the afternoon I–1 readings was 4.1 mg/l (N = 28). Even turning the pump on at 12:00 h does not avoid below-standard water being pumped to the lake for a considerable amount of time per day. However, the advantage of turning the pump on at the later time is probably most significant during the months of July to October because of the increased oxygen demand associated with anaerobic waters.

Although the lake DO has its own cycles as seen in Fig. 23, on average, its worst time of year is also during the late summer to fall period. The average DO at the SML–1 station from July to September for 1990 and 1991 was 5.0 mg/l. For July to October it was 5.3 mg/l.

The results of all phases of the study give a clear picture of the daily and seasonal trends in water quality over almost a 3 year period. The next chapter deals with how these results compare to the results obtained from the monthly testing conducted to comply with the RWQCB permit.

CHAPTER 5

ADEQUACY OF MONTHLY AS COMPARED TO WEEKLY TESTING

The second question addressed in this study relates to the adequacy of monthly testing as specified in the RWQCB permit. Do the results of monthly testing give sufficient information about the conditions in the lake to analyze water quality and to make management decisions to maintain the standards established in the permit? Do the weekly data collected for this study give significantly different results from the monthly data collected by SEL to comply with the permit obligations?

Problems were encountered in attempting to compare the sets of data at each station because of differences in data collection methods, uncertainty about quality control for the monthly data which were not all collected by the same individual, and the fact that the time of day of testing for the monthly data was on a more random basis than the weekly testing. The weekly data at each station were always collected at approximately the same time of day. The monthly data were sometimes collected during the morning, while at other times they were collected during the afternoon. Stuart (1987), who did a study of the Sailing Lake in 1985-86, also noted the uncertainties of using SEL data because of his lack of knowledge of quality control methods used by SEL testers. Because of these concerns, the weir station (E-1) was chosen as the one at which the methods of data collection were most similar for the 2 sets of data. Secchi depth was excluded because of a difference in the precision of the measurements and the dependence of that parameter on the eyesight of the observer.

Fig. 27a-d includes plots of the weekly data from March 1990 to December 1991 along with the monthly data for that period of time for the parameters DO, temperature, salinity, and pH. There are 22 values for the monthly data for all parameters except temperature which has 33 because the RWQCB permit requires 2 temperature measurements per month from May to September at E–1 (RWQCB 1986). There are 89 values for the weekly data except for pH which has 62. The weekly data were always collected between 9:30 and 12:00 h. The monthly data were collected between 7:40 and 10:40 h until April 1991. From May to December 1991 data were collected between 9:30 and 16:40 h.

Dissolved Oxygen

For DO the monthly data seriously underestimated the variability of the data as compared to the weekly data. The range of the weekly data was 14.1 mg/l (maximum—17.4 mg/l, minimum—3.3 mg/l) while the range of the monthly data was only 1.8 mg/l (maximum—6.4 mg/l, minimum—4.6 mg/l). The standard deviation of the weekly data was 1.6 and only 0.36 for the monthly data. The average weekly DO was 6.5 mg/l, while the average monthly DO was 5.3 mg/l. The main reason for the difference was the fact that the monthly schedule of testing completely missed the extremely high values that occurred during the 3 week period at the end of March and the beginning of April 1991 when an algal bloom occurred in the lake. The importance of time of day of testing is illustrated by the results in August and September 1991. Between

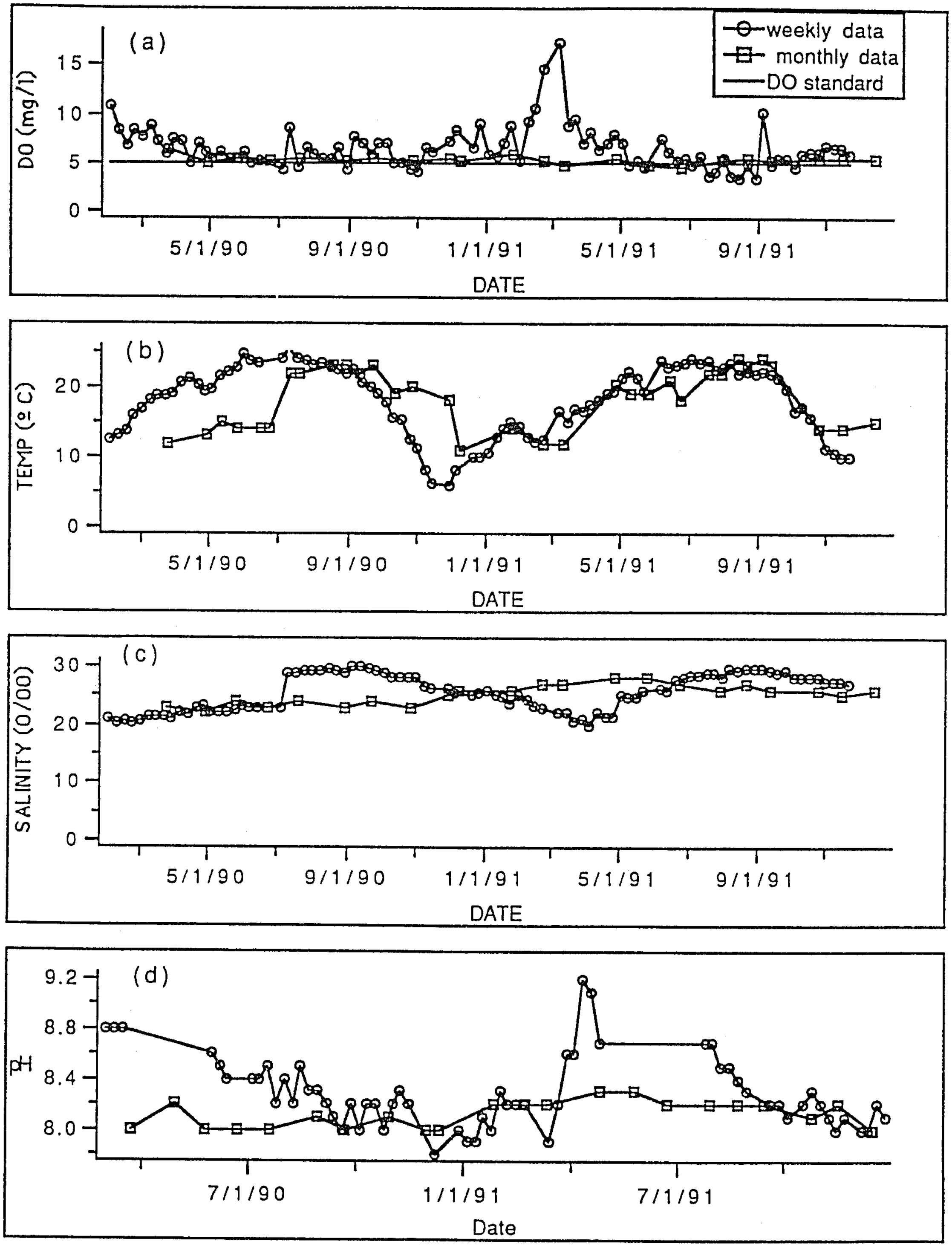

Fig. 27a-d. E-1 weekly data compared to E-1 monthly data for (a) DO (b) temperature (c) salinity and (d) pH. Monthly data from ERA, Shoreline at Mountain View: Quarterly Reports on Water Quality Observations (Davis: ERA, 1990-1992).

August 15 and September 27, 1991 the weekly values, which were always taken in the morning, were below the 5.0 mg/l standard 6 out of 7 times. On the other hand, the monthly values for August and September were 5.4 mg/l and 5.2 mg/l, respectively. Beginning in July 1991 the monthly values were always collected during the afternoon. The diel results discussed earlier show that because of the daily DO cycles that occur in the lake, it is likely that DO was below 5.0 mg/l during the morning on the dates when the monthly testing was done during August and September.

For DO the once a month testing schedule specified in the permit is apparently inadequate to give results which accurately portray the variations which can occur in the lake. The fact that time of day of testing is not specified in the permit also can lead to misleading data. In order to sample the lowest DO values that may occur in the lake, morning readings should be specified.

Temperature

Fig. 27b shows the weekly and monthly temperature data. The seasonal cycles show up in both sets of data for this parameter. It is not clear why the monthly data showed such a sudden jump between June and July 1990 (14 to 22 ºC) when the weekly data were showing a much more gradual increase. After July 1990 the seasonal variations were similar for both sets of data. However, the monthly data underestimated the minimum for the year because there were no data collected when the coldest weeks occurred in January 1991 (the monthly minimum was 11 ºC in December 1990; the weekly minimum was 6.0 ºC on January 3, 1991). The average for both sets of data was the same at 18.2 ºC.

For temperature, a parameter whose seasonal variation is much more regular than the more unpredictable DO, the monthly schedule of testing gave a reasonably accurate approximation of the more detailed results of the weekly schedule.

Salinity

Fig. 27c shows the salinity comparison for the weekly and monthly data. It should be noted that the monthly data were reported to the nearest part per thousand while the weekly data were measured to the nearest tenth of a part per thousand. As explained in the weekly results described earlier, the sudden jump in the weekly data on August 11, 1990 occurred after the meter was serviced for the first time. For the rest of the summer and fall of 1990 the weekly data stayed very near to the higher level. The monthly data never reached that high of a level in 1990.

The monthly readings did not show as much variation as the weekly readings. The monthly values varied from 22 to 28 $^{o}/oo$ while the weekly values ranged from 19.8 to 29.9 $^{o}/oo$. In the spring of 1991 the data sets showed an opposite trend. The monthly data increased to a maximum for the year in April which was repeated in May. At the same time the weekly data were declining to a minimum for the year on May 2. The reason for this discrepancy was not apparent. Finally, in the summer of 1991 the data converge to similar readings from July onward. The averages for the 2 sets were close. The monthly average was 25.3 $^{o}/oo$, and the weekly average was 25.6 $^{o}/oo$.

Although the salinity data sets showed seasonal inconsistencies, the ranges of the 2 sets of data were similar. Salinity must be measured to calculate accurate DO values, so if the DO testing requirement was increased to gain a more accurate assessment of the lake's oxygen content, then salinity would need to be measured on the same schedule.

pH

Fig. 27d shows the results for pH for the monthly and weekly data sets. Although there were 2 large gaps in the weekly data as described earlier, it is clear that the variation in the weekly data was much greater than the monthly data's variation. The weekly data varied between 7.8 and 9.2 while the monthly data only varied between 8.0 and 8.3. The fact that there were no monthly readings at the time of the algal bloom in late March and early April of 1991 would account for the lack of a jump in pH at that time as there was an algal bloom occurring at that time as described above under DO. DO and pH both increase when "vigorous photosynthesis occurs in productive waters" (Goldman and Horne 1983, 98).

The objective for pH for bay waters according to the Water Quality Control Plan for the San Francisco Bay Region (RWQCB 1986) is to maintain it at a level between 6.5 and 8.5. According to the weekly data, the lake exceeded the maximum by as much as 0.7 units while according to the monthly data the objective was not violated at all during 1990 and 1991.

Conclusion

The weekly testing did a much better job of indicating that the DO and pH standards were violated for significant periods of time in the lake during the period of testing compared to the monthly testing. The weekly testing detected the rapid changes that can occur in the lake which may be detrimental to the aquatic organisms living in the lake and thus to the bird life (such as the endangered least tern) dependent on the lake organisms as a food source. Since the lake is also a discharger to the bay waters, poor water quality conditions in the lake could also impact the South Bay negatively. For these reasons a more frequent testing schedule for these parameters, especially DO, should be required in the lake permit.

CHAPTER 6

WATER QUALITY EFFECTS OF MANAGEMENT PRACTICES

The water level in inner Charleston Slough and the timing of water pumped to the sailing lake are 2 variables over which Shoreline has control as the water delivery system is now constructed. This chapter analyzes the effect on water quality of managing these parameters.

Effects of Water Level Management

The upper water elevation adjustment at the inlet/outlet structure at the entrance to inner Charleston Slough regulates the water level in the slough by controlling the amount of water that enters through the gate when water is flowing into the slough. When an adjustment is made, it takes an unknown amount of time for the slough level to stabilize at a new level. If the level is lowered, more daily fluctuation is expected than at the previous level (Posternak 1988b, 2–3).

The unit on the staff gauge at the lake supply pump is called the Mountain View City Datum (MVCD). It was arbitrarily chosen for the staff gauges at Shoreline so that water level readings would be near 100 ft. This choice avoids the necessity of using negative numbers which would be the case if the National Geodetic Vertical Datum (NGVD) had been used as the zero point on the gauge. The 100 ft level is approximately 100 ft above NGVD and 96 ft above mean lower low water according to a survey done by Harrison, Teasley, and Associates during 1990.

Fig. 28 shows the water levels in the slough as measured at the staff gauge at the Charleston Slough lake supply pump, along with the monthly DO and temperature readings from SEL, from April 1986 when water quality measurements began to be made on a monthly basis until the end of 1990. Water level data from April 1986 to August 1988 were collected by representatives of the SCVAS about twice a month (Bousman 1989). There are 51 values in this data set. From February 25, 1988 until December 31, 1989 the daily level measurements made by the rangers at Shoreline are included. During the water level lowering experiment in 1988, Shoreline personnel took water level readings every 1 to 2 hours while the pump was on. During the period before and after the experiment, they took level readings twice a day. These data are unpublished and were obtained from the Shoreline office, City of Mountain View. Each water level value on the graph taken from the Shoreline personnel's data is the average of all readings for the particular date. The 1990 level data came from the author's weekly readings.

The upper water level elevation adjustment on the inlet/outlet structure was adjusted downward twice by a total of 0.30 ft on April 11 and April 26, 1988 (Posternak 1988b, 2). Two days after the second adjustment, the water level dropped 1 ft from morning to evening, the largest daily fluctuation recorded during the experiment. The next day the elevation adjustment was adjusted upward 0.05 ft, and on May 14 another upward adjustment of 0.025 ft was made (Posternak 1988b, 2). When the water level dropped to near 98.00 MVCD, land bridges formed causing the northern end of the slough to become isolated from the southern end where the lake supply pump is. Under this condition the level in the pump end of the slough began to drop more rapidly to a level too low to

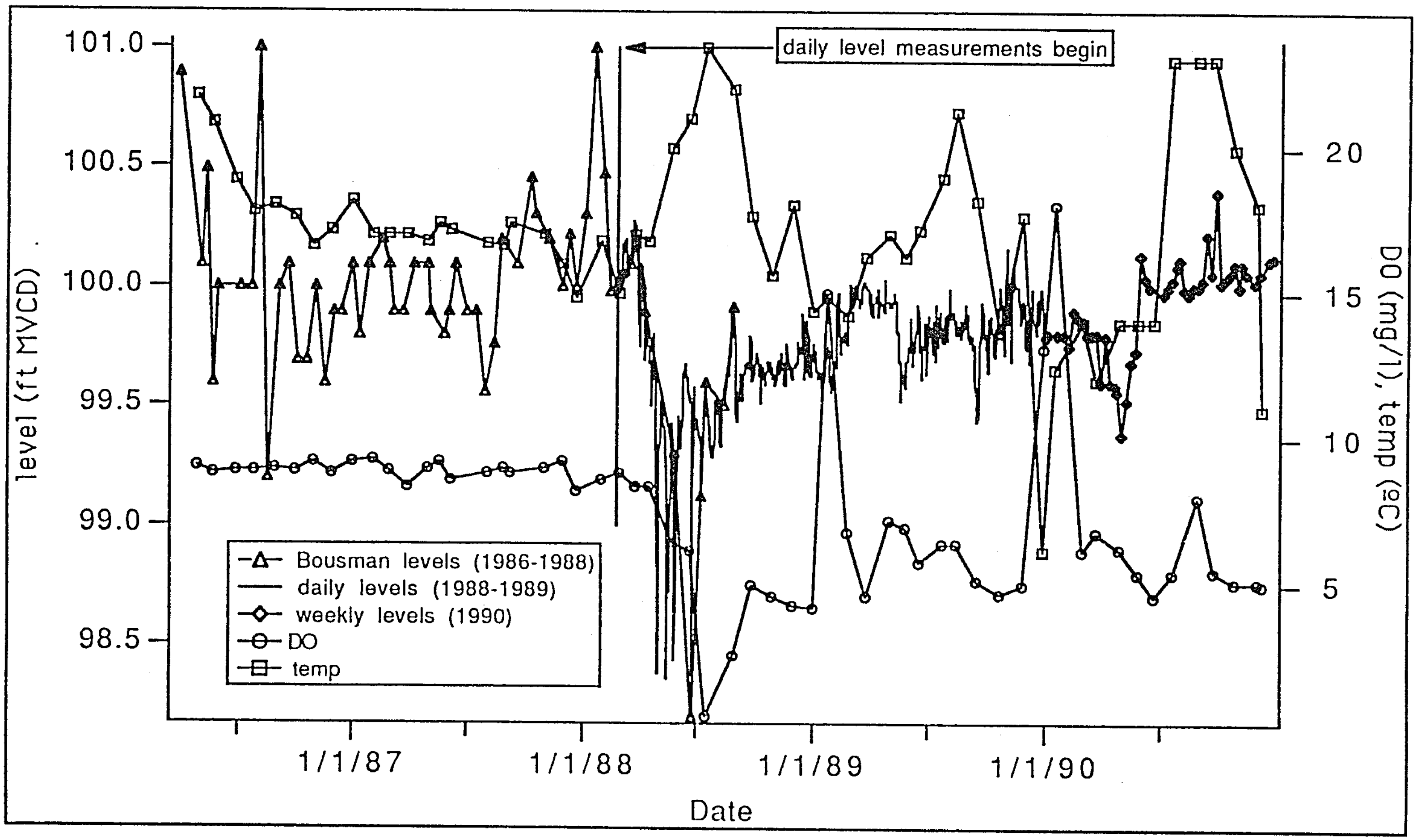

Fig. 28. Water levels, monthly DO, and monthly temperature at Charleston Slough (I-1) from 1986-1990. Level data from 1986 to August, 1988 from Bill Bousman, Unpublished data (Palo Alto: SCVAS, 1989). Level data from February 25, 1988 to December 31, 1989 from Shoreline at Mountain View, Unpublished daily data (Mountain View: Shoreline at Mountain View, 1988-1989). Level data from January 1990 to December 1990 from weekly data collected by author. DO and temperature data from ERA, Shoreline at Mountain View: Quarterly Reports on Water Quality Observations (Davis: ERA, 1986-1991).

operate the pump. This is why the upward adjustments were made (Posternak 1988b, 3–4). In Fig. 28 this period is indicated by the 4 spikes when the average level dropped below 98.50 MVCD, the last of which occurred on May 26, 1988. After that date the level never again dropped below 99 ft.

Table 8 summarizes the data in Fig. 28 according to the time periods before, during, and after the water level lowering experiment in inner Charleston Slough and the sources of level data. The average water level from April 11, 1988 to September 3, 1988 dropped to 99.42 MVCD, a decrease of 0.64 ft from the 1986–88 pre-experiment period. Before the experiment the daily fluctuation was typically near 0.10 ft (Posternak 1988a). The average daily fluctuation between April and September increased to 0.22 ft. Since September 1988 the daily fluctuation has returned to about what it was before the experiment. From September 1988 to the end of 1989 the average daily fluctuation was 0.11 ft.

The table and graph show that before the water level experiment began, the monthly DO and temperature readings were quite stable. DO was near 100 % saturation for all measurements. The monthly DO and temperature readings became unstable at the same time the experiment started. The minimum monthly DO ever recorded occurred in July 1988 (0.5 mg/l) as did the maximum temperature (24.5 ºC). The measurements on this date were made at 7:30 h. Temperature and DO have been seasonally cyclical since 1988. The DO readings showed extremely high peaks in January with values varying between 4 and 8 mg/l the rest of the year. The average DO for 1989 and 1990 increased from 1988 but not back to the level before April 1988 despite the fact

Table 8.--Charleston Slough I-1 Water Levels, Monthly DO, and Monthly Temperature Averages and Ranges

Dates	Level ave. (MVCD)	Level range (MVCD)	DO ave. (mg/l)	DO range (mg/l)	Temp. ave. (ºC)	Temp. range (ºC)
4/86-4/88	100.06	99.2-101	8.9	8.2-9.3	17.4	14.8-21.8
4/88-12/88	99.53	98.36-99.92	4.7	0.5-8.4	18.8	14.4-23.4
1/89-12/89	99.82	99.44-100.16	7.3	4.6-15	16.0	6.2-21.2
1/90-12/90	99.92	99.38-100.40	6.8	4.6-18	16.5	11-23

Data Sources: Levels (4/86-4/88) from Bill Bousman, Unpublished data. (Palo Alto: SCVAS,1989); Levels (4/88-12/89) from Shoreline at Mountain View, Unpublished daily data. (Mountain View: Shoreline at Mountain View, 1988-1989); Levels (1/90-12/90) from weekly data collected by author; and DO and temperature data from ERA, Quarterly Reports on Water Quality Observations (Davis: ERA, 1986-1991).

that the average temperatures during 1989 and 1990 were lower than they were before April 1988.

The water quality readings recorded during the summer of 1988 led the Shoreline staff to the assumption that there was a direct correlation between the water level and the DO in the inner slough. It was assumed that the previous stable readings near 100 % saturation would return if the water level was returned to the level it was prior to the beginning of the experiment (Posternak 1988b, 5; Trulio 1989a, 3). Twice in February 1989 the water level elevation adjustment was adjusted upward by a total of 0.2 ft to achieve this result (Trulio 1989b, 2). Since then, further adjustments have been made in the effort to keep the level of the inner slough near 100 MVCD (Trulio 1991, 4).

Table 9 shows the variances for the averages of each year's DO data from 1987 to 1990 and the F statistics for comparing those variances. Because of the great differences in the variances, it isn't possible to compare the data before 1988 to the data since 1988 using t–tests. The F statistics for comparing years since 1988 are acceptable. The t statistic for 1989 versus 1988 is 1.2. The t statistic for 1990 versus 1988 is 0.8. Neither of these is significant at an alpha of 0.10. Based on the small amount of monthly data available, there was not a significant increase in average DO values in the slough after raising the water level back to approximately what it was before the water lowering experiment.

The weekly morning data also show (Fig. 22) that DO and temperature were seasonally cyclical during 1990 and 1991. They also reveal that extremely low DO readings (near 0 mg/l) were recorded routinely during the summer months. The diel and all day data, discussed earlier in Chapter 4,

Table 9.--Variances of Yearly Average Monthly DO for 1987 to 1990 with Comparable F Statistics

Year	Average (mg/l)	Variance	Years compared	F statistic
1987	8.9	0.1	1988/1987	63.0
1988	5.7	6.9	1989/1987	100.7
1989	7.3	11.0	1990/1987	121.8
1990	6.8	13.4	1989/1988	1.6
			1990/1988	1.9

show that typically there were also wide variations in DO and temperature diel cycles with the greatest diel variations occurring during the summer months.

An alternative hypothesis about the lack of large DO variations in the slough during the 2 years of monthly testing prior to the water level lowering experiment that seems plausible is that there were low DO readings all along in the slough during the summer, but that the infrequent testing schedule that did not specify the time of day of testing missed, until 1988, what is a routine occurrence in the slough in the early morning hours. Before April 1988 the time of day of testing was generally later than after April 1988. For dates before April 1988 for which times were specified on the data sheets, 13 were after 10:00 h while 9 were before 10:00 h. From April 1988 until December 1990, 28 times the readings were made by 10:00 h and only 4 times after 10:00 h..

During 1986–87 Lonzarich (1989) did a study of some of the Leslie salt ponds further south in South San Francisco Bay near Alviso. He observed wide fluctuations in DO values over the course of a day's testing. For example, on one day during May 1986, DO varied between 2.3 and 12.2 mg/l between 7:00 and 16:00 h in Leslie Pond A9 (Lonzarich 1989, 44), a pond which is similar to Charleston Slough in depth, salinity, and algal growth.

Using aerial photographs, Posternak (1988a, 4) estimated that there was little change in the marsh vegetation in inner Charleston Slough between 1984 and 1987. Since at least 1985, heavy algal mats have been observed in the slough during the summer months (Krone and Cheney 1985, 22). This evidence indicates that it is possible that the pattern of extreme diel changes in DO observed from 1988–1991 occurred during earlier summers in Charleston Slough, but just wasn't recorded.

The assumption that maintaining the water level in the inner slough at about 100 MVCD would have the effect of increasing and then stabilizing DO concentrations in the slough is not supported by the data that are available. Apparently the water level management policy that has been in effect since 1989 has had little influence on DO concentrations in Charleston Slough. Thus, changing the slough's water level will not necessarily affect the amount of oxygen delivered to the lake.

The problems associated with basing management decisions on assumptions based on the sketchy monthly data for 1986–88 are evident. Depending on the time of day of testing, a single monthly reading could lead to widely varying results and very different conclusions about the condition of the slough with regard to DO.

Effects of Time of Day of Pump Operation

This section deals with the analysis of the data collected during phase 2 of the study to answer the question: Does changing the pumping time to the lake have a significant effect on the amount of oxygen that is pumped into the lake?

Amount of Oxygen Pumped from Charleston Slough to the Sailing Lake (P)

Fig. 29 shows the results from the calculation of the amount of oxygen pumped to the Sailing Lake from Charleston Slough per day under the different theoretical pumping schedules as well as the actual oxygen pumped for the days of testing. Values were obtained as described in Chapter 3 under the corresponding methods section.

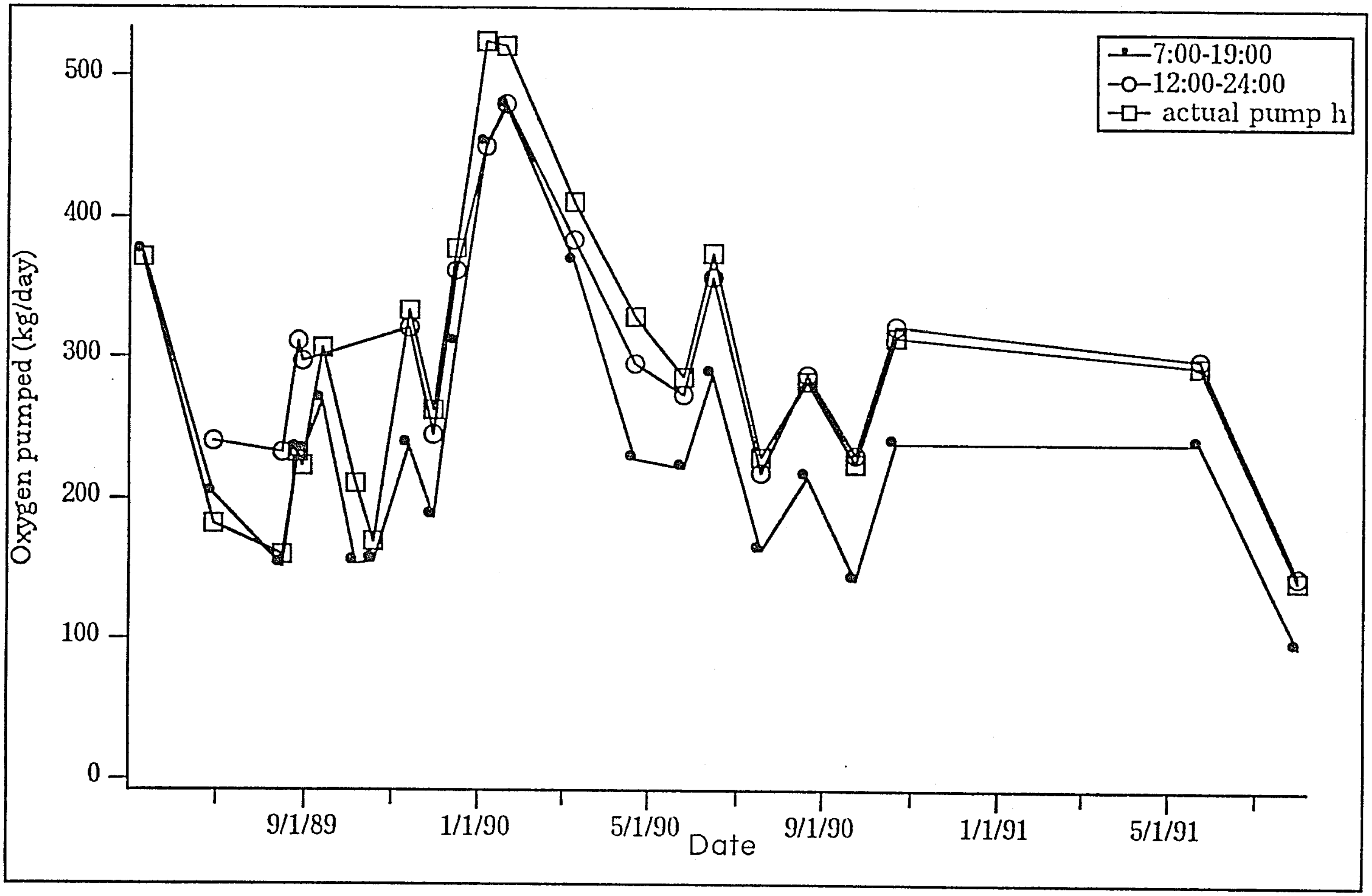

Fig. 29. Actual oxygen pumped to Sailing Lake per day with theoretical oxygen pumped for 2 different 12 hour pumping schedules shown. Actual pumping hours varied as described in text.

Until the end of August 1989, the pumping schedule was from 7:00–19:00 h. From the middle of September 1989 until November 1989, the pump was operated for approximately 12 hours per day with a starting time between 9:45 and 12:15 h depending on the availability of park personnel. During November 1989 an automatic shutoff timer was put into operation with a stopping time around midnight which has remained in operation since that time, but the starting time has varied between 10:00 and 13:30 h. Because the actual hours of pumping were often greater than 12 hours after November 1989, the actual pump hours oxygen per day are often greater than the 12:00–24:00 h pumping schedule in Fig. 29.

Fig. 29 shows that the winter months of December to March showed a considerably different pattern than the rest of the year for the amount of oxygen pumped to the lake. The oxygen pumped per day was generally higher than the rest of the year under either pumping schedule, and the difference between the pumping schedules was much smaller. As previously discussed, these were the only months when DO readings did not drop below the 5.0 mg/l standard at any time during diel testing.

Table 10 gives the averages of the oxygen input to the lake under the 2 pumping scenarios divided into the April-November period when minimum DO dropped below 5.0 mg/l on most dates tested and the December-March period when the minimum DO never dropped below 5.0 mg/l. Also the average oxygen outflow from the weir for the same periods is included.

The difference between the overall average of oxygen pumped for the 2 pumping schedules during the April to November period was considerably

Table 10.--Average Oxygen Pumped (P) to Sailing Lake Per Day Under Different Pumping Schedules and Corresponding Average Oxygen Weir Outflow (W)

	Average O_2 pumped or outflow (kg)	Range of values (kg)	Number of values
If pumping 7:00-19:00 h	240	95-480	23
April-November	210	95-370	19
December-March	400	310-480	4
If pumping 12:00-24:00 h	300	140-480	19
April-November	270	140-350	15
December-March	420	360-480	4
Weir outflow 7:00-19:00 h	110	60-160	14
April-November	100	60-160	10
December-March	120	100-140	4
Weir outflow 12:00-24:00 h	100	60-1130	9
April -November	100	60-130	8
December-March	130	130	1

Note: April-November includes values recorded during those months from 1989 to 1991. December-March includes values from December 1989 to March 1990 only.

greater than during the December to March period. The average of oxygen pumped during the December to March period was very much greater than the April to November period for both pumping schedules. The average outflow during the December to March period from 7:00 to 19:00 h was also greater than during April to November but by a much smaller difference than the comparable inflows from the pump.

A paired sample t test between the P values for the 2 pumping schedules for dates when testing occurred between at least 7:00 and 24:00 h ($N = 19$) showed that the 12:00–24:00 h schedule very significantly delivered more oxygen to the lake. The t statistic is 10.6 which is significant ($p < 0.0005$). The paired sample t statistic for comparing P values for the 2 pumping schedules for dates between December and March ($N=4$) is 2.19 ($p = 0.116$) which is not significant. On average the 12:00–24:00 h schedule delivered 27% more oxygen to the lake. Between April and November the average difference between pumping schedules was 33%. There is little doubt that the 12:00–24:00 h pumping schedule will deliver more oxygen to the lake than the 7:00–19:00 h schedule at virtually any date between April and November. The final section in this chapter deals with the attempt to quantify the contribution to the lake DO levels of different pumping schedules as compared to the other sources of oxygen to the lake.

Comparison of Oxygen Input to Lake from Various Sources

Amount of Oxygen in the Sailing Lake at Any Given Time (A)

Table 11 shows the results of the calculation of the total amount of oxygen in the lake (A) for each round of testing for those dates when testing was

Table 11.--Total Oxygen in Sailing Lake (A) for Each Round of Testing Calculated from Readings at SML-1 and SML-2 Stations

Time	Oxygen (1000 kg)								
	11/14/89	11/30/89	6/14/90	7/19/90	8/20/90	9/24/90	10/22/90	5/22/91	7/30/91
7:30-8:30	6.7	4.7	5.4	4.6	4.4	5.5	5.9	6.9	5.2
10:30-11:30	6.9	4.9	n.d.	4.4	4.5	5.6	6.1	7.0	5.5
13:30-14:30	6.6	4.9	n.d.	4.7	4.6	5.9	7.0	7.1	6.0
16:30-17:30	7.4	4.8	6.5	5.4	4.9	5.9	8.1	8.3	6.9
19:30-20:30	7.1	4.8	6.4	5.9	6.2	7.2	7.9	7.2	5.6
22:30-23:30	7.1	n.d.	5.2	5.4	5.7	5.9	6.6	7.6	5.7
1:30-2:30	n.d.	n.d.	5.6	4.9	5.5	5.3	7.0	7.6	5.2
4:30-5:30	n.d.	n.d.	5.5	5.1	5.0	5.5	7.1	7.3	5.0

done at both the SML–1 and SML–2 stations. The calculations were made as described in the corresponding section of Chapter 3. The uncertainty in these calculations may be considerable judging that the calculation extrapolates to the whole lake from only 2 stations with no values obtained from the middle of the lake. The fact that the lake is so well mixed, and that in general there were no large differences between the stations tested at any particular time of day may mitigate the problems with using only 2 stations. The results are consistent with the results for each station's DO–time of day graphs discussed in Chapter 4. For example, there was a substantial drop in the amount of oxygen in the lake between November 14 and November 30, 1989. The November 30, 1989 data are the most unusual showing hardly any change during the 12 hour period of testing. Otherwise, the daily cycle is fairly consistent. The earliest reading is generally a relative minimum. The oxygen then increases to the maximum which occurs either at 16:30–17:30 h or at 19:30–20:30 h and then decreases in the evening. The unusual increases in the late night values that occurred on 3 out of the 7 dates when diel testing was done reflect the readings at SML–2 where it was common for DO to increase after dark. If more stations from different portions of the lake had been included, the after dark increases in DO for the whole lake may have been eliminated.

Change in A During Various Time Periods (ΔA)

Table 12 shows the results for the change in total oxygen (ΔA) in the lake computed by subtracting the A values for the time periods indicated as explained in the corresponding section in Chapter 3. The ΔA_{8-20} results show that during 1990 the daily oxygen changes in the lake appeared to be greater

Table 12.--Estimates of Daily Changes in Sailing Lake Oxygen (ΔA) and Sum of Inputs from Atmospheric Exchange and Reactions ($\Delta(D + R)$) for Different Time Periods

Dates	$\Delta A_{8\text{-}20}$	$\Delta A_{11\text{-}23}$	ΔA_{diel}	$\Delta(D{+}R)_{8\text{-}20}$	$\Delta(D{+}R)_{11\text{-}23}$	$\Delta(D{+}R)_{diel}$
11/14/89	370	240	n.d.	n.d.	n.d.	n.d.
11/30/89	22	n.d.	n.d.	n.d.	n.d.	n.d.
6/14/90	980	n.d.	87	830*	n.d.	−110*
7/19/90	1300	1000	550	1300*	890*	500*
8/20/90	1800	1200	580	1700*	1000*	470*
9/24/90	1600	330	−100	1600	210	−180
10/22/90	2000	470	1200	1900	300	1100
5/22/91	220	610	320	120	450	220
7/30/91	470	270	−130	460	230	−130

Notes: Units of all values are in kg of oxygen. Values are estimates of the actual changes in the lake for each date.

*These values use the average weir output for the time period (from dates when.data were available) for dates when no weir readings were available during that period of time. See chapter 3 for explanation of calculations.

than in either of the other years of the study. The smallest increase in 1990 (980 kg) was more than twice as much as the largest increase in either of the other 2 years (470 kg). Although the data are sparse, this may be an indication of the effect of a sea lettuce algal bloom that occurred in the lake during the summer of 1990. No such bloom was observed during either 1989 or 1991. The ΔA_{diel} results show that there can be a wide variation in the net change in oxygen over the course of almost a 24 hour period. On 2 occasions the lake apparently lost oxygen over the course of the day, while on October 22–23, 1990 it had a large increase. This is a reasonable result based on the observations of fairly rapid increases or decreases in DO observed at the lake stations over time periods of 4 days to a week (see Chapter 4).

<u>Net of Input from Pump and Outflow from Weir (P - W)</u>

Table 13 shows the values of P, W, and P – W used to calculate the $\Delta(D + R)$ values reported in Table 12. All of these calculations are explained in the corresponding sections in Chapter 3. The values of P and W are all actual values for the time periods of testing at the stations in the lake except that the average W for dates when weir data are available are used for the starred values when no weir data were available for a particular date or time period. This approximation does not introduce significantly more error into the calculations since the values of W are small in comparison to the other quantities in the calculation and show a much smaller variation between dates than the other quantities.

For any particular time period and date, P is always greater than the corresponding W. (P – W) for the 11:00–23:00 h time period is always greater

Table 13.--Oxygen Input from Pump (P), Oxygen Outflow Through Weir (W), and Net Change from Input and Outflow (P -W) for Given Time Periods Corresponding to ΔA Times in Table 12

Dates	P_{8-20}	W_{8-20}	$(P - W)_{8-20}$	P_{11-23}	W_{11-23}	$(P - W)_{11-23}$	P_{diel}	W_{diel}	$(P - W)_{diel}$
6/14/90	260	110*	150*	n.d.	n.d.	n.d.	370	170*	200*
7/19/90	160	110*	50*	210	110*	100*	230	170*	60*
8/20/90	210	110*	100*	270	110*	160*	280	170*	110*
9/24/90	150	90	60	210	90	120	230	150	80
10/22/90	210	130	80	290	130	160	310	210	100
5/22/91	210	120	90	280	120	160	290	200	90
7/30/91	100	90	10	130	90	40	140	150	—10
Averages	190	110	80	230	110	120	260	170	90

Notes: Units of all values are in kg of oxygen. P values are estimates of the actual oxygen input to the lake for each date for the same time period as the corresponding ΔA in Table 12. W and (P — W) values are estimates of actual weir outflow and net change due to input and outflow .

*These values use the average weir outflow for the specified time period (from dates when data were available) for dates when no weir readings were available during that period of time. See chapter 3 for explanation of calculations.

than the corresponding (P – W) for the 8:00–20:00 h time period. The pump was turned on between 10:00 and 12:00 h for these dates and went off at midnight. The average weir outflow for 12 hours varies little regardless of the time of day. In only one case was there a negative $(P - W)_{diel}$. That occurred on the date when the lowest maximum DO at the pump of the entire study occurred.

Net Change in Oxygen Due to D and R (Δ(D + R))

Table 12 includes the (Δ(D + R) calculations which are estimates of the net change in oxygen in the lake due to atmospheric exchange plus photosynthesis for the time periods shown. All of the $\Delta(D + R)_{8-20}$ values are greater than the $\Delta(D + R)_{11-23}$ except on May 22, 1991. This is expected since the 8:00–20:00 h time period coincides with the approximate hours when photosynthesis is occurring during the summer months. The May 1991 date had an unusual pattern. The maximum A occurred at the 16:30–17:30 h round of testing, dropped 1100 kg by the 19:30–20:30 h round, and then increased 400 kg by 22:30–23:30 h thus making the ΔA_{11-23} greater than ΔA_{8-20}, on this date only. The $\Delta(D + R)_{diel}$ values show considerable variation with a range of –180 to 1100 kg indicating the wide range of possibilities for changes in the lake over the course of a day.

Table 14 shows the ratios of Δ(D + R) to ΔA for the two 12 hour time periods considered in Table 12. The results for $\Delta(D + R)_{8-20}/\Delta A_{8-20}$ are very steady except for the May 1991 date which was unusual for the reason described above. Excluding the May 1991 value, the average is 0.95. These

Table 14.--Ratio of $\Delta(D + R)$ to ΔA for the Dates and Time Periods Shown in Table 12

Dates	$\frac{\Delta(D + R)_{8\text{-}20}}{\Delta A_{8\text{-}20}}$	$\frac{\Delta(D + R)_{11\text{-}23}}{\Delta A_{11\text{-}23}}$
6/14/90	0.85*	—
7/19/90	0.96*	0.90*
8/20/90	0.95*	0.87*
9/24/90	0.97	0.64
10/22/90	0.96	0.65
5/22/91	0.56	0.74
7/30/91	0.98	0.83
Averages	0.89	0.77

*These values are calculated using the average weir values as explained in Tables 12 and 13.

results show that reactions and/or atmospheric exchange are normally the dominant causes in daily changes of total oxygen in the lake.

The amount of oxygen pumped to the lake per day is small compared to the increase in oxygen due to photosynthesis and reaeration regardless of the time of day of pumping. This result was expected because photosynthesis is expected to be the major source of oxygen in lakes. However, the 12:00–24:00 h pumping schedule does provide the optimum amount of oxygen under the current conditions. It also has the advantage of avoiding pumping anaerobic waters during the late summer and fall which increases the oxygen demand at a greater rate than would be expected just from dilution. It may also reduce the amount of nitrogen and phosphorus nutrients delivered to the lake significantly because studies (Welch 1980, 66–75) have found that nitrogen and phosphorus compounds are released at a much greater rate from the substrate under anaerobic conditions than under aerobic conditions. This possibility is taken up under the section on further research possibilities in Chapter 7.

CHAPTER 7

SUMMARY AND RECOMMENDATIONS

This study set out to answer several questions. Each is repeated below with the major results summarized. Table 15 shows a brief summary of the major findings.

Question 1: Daily and Seasonal Cycles

What are the daily and seasonal cycles in the Charleston Slough and the Sailing Lake water quality parameters that would be revealed by a more extensive testing program, and what factors influence these cycles?

Daily and Seasonal Cycles: Findings

As water enters Charleston Slough at G-1 and progresses through the system, daily DO cycles change substantially depending on the nature of the particular environment of each part of the Shoreline system.

The daily DO cycle in the water entering at G-1 is primarily influenced by the tidal cycles of San Francisco Bay. DO is higher near the time of high tide and lower near the time of low tide. DO levels of water entering the slough are rarely below the DO standard set for the lake. However, the bay water has high nutrient loadings and is very turbid which helps to stimulate the heavy blooms of algae that occur in the slough during both the summer and winter.

Once water is in the shallow pond environment of the inner slough, the DO cycle is primarily influenced by the photosynthesis/respiration cycle of the heavy concentrations of algal growth stimulated by the favorable conditions for

Table 15.--Summary of Major Findings of the Study

Topic	Major Findings
Diel and Seasonal Cycles	1. Diel DO cycles mainly influenced by: • tidal cycles outside gate (G-1). • photosynthesis/respiration cycles in inner Charleston Slough (O-1, A-1, and I-1). • artificial circulation from pumping as well as photosynthesis/respiration cycles (lake stations). 2. DO standard (5.0 mg/l) is: • rarely violated for incoming bay water (G-1). • violated daily in Charleston Slough during summer when extreme diel DO cycles occur with anaerobic conditions normal in morning July to October. • violated often in the lake during summer but with less extreme diel cycles than in slough. 3. Inverse relationship between morning minimum DO and morning temperature throughout the year at I–1. 4. Pumping 12 hours per day prevents stratification in lake during all seasons.
Monthly vs. Weekly Testing	1. Weekly testing reveals much larger variations in DO and pH in lake than monthly testing does. 2. Important to do morning testing to record lowest DO.
Water Quality Effects of Management Practices	1. Water level management of Charleston Slough has no apparent impact on stability of DO in slough. 2. 12:00-24:00 h pumping schedule delivers 33% more oxygen to lake from April to November than 7:00-19:00 h schedule. 3. Lake photosynthesis/respiration cycle has much greater impact on daily changes in lake DO than oxygen input from pumping action.

algal blooms in the slough. Extremely large diel variations in DO occur during the summer as the DO varies sinusoidally. DO is routinely near 0 mg/l in the morning and highly supersaturated in the afternoon. Charleston is a stressful environment for organisms living in the water column or the substrate. Extremely high DO readings can also occur during the winter, but since respiration and decomposition rates are so much slower during the winter, DO does not drop below 5.0 mg/l during these months even in the early morning hours.

The 12 hour per day pumping schedule prevents stratification from occurring either in the channel to the pump or in the lake. The lake's diel DO and temperature cycles are muted compared to the pump. However, there are small but consistent differences between the lake stations in daily temperature and DO patterns. The SML–2 station has an unusual pattern of increasing DO after dark apparently due to the circulation patterns set up by the pumping action.

At the pump, morning minimum DO varies inversely with the morning water temperature. When the water temperature reaches approximately 15 ºC in the spring, then the morning minimum drops below 5.0 mg/l. The morning minimum stays below 5.0 mg/l until the water temperature drops back to about 8 ºC in the winter. From July to October the DO levels are especially poor in the slough during the morning hours when conditions become anaerobic because of the respiration and rapid decomposition of algal mats. The lake's DO is also on average at its lowest during the same period of the year.

Question 2: Adequacy of Monthly as Compared to Weekly Testing

Is the schedule of testing required in the RWQCB permit adequate to give sufficient information on which to base analysis of water quality and subsequent management decisions for maintaining the lake system at the standards established in the permit?

Major Finding

For DO and pH, 2 parameters for which standards are set in bay waters, the monthly testing schedule gives inadequate information about the variations that occur in the lake. The weekly testing schedule uncovered variations which showed that these parameters can change significantly from week to week. DO may drop below the 5.0 mg/l standard for 1 to 2 weeks at a time and not be detected by a monthly schedule. In order to gain adequate knowledge on which to base management decisions, a more frequent schedule of testing is needed for these parameters. The weekly schedule of testing used for this study gives much more information than the monthly schedule. The time of day of testing should be during the early morning because that is when DO is at its daily minimum.

For more predictable parameters such as temperature, the monthly data give a reasonable approximation of the more detailed data obtained from weekly testing.

Question 3: Water Quality Effects of Management Practices

Can the slough and lake water quality be influenced positively by the simple, inexpensive management strategies available in the system as it now exists?

a. Specifically, does increasing the water level in Charleston Slough by adjustments in the hydraulic control structure at the entrance of the inner slough have a significant impact on DO levels in the slough?

b. Does changing the pumping time to the lake have a significant effect on the amount of oxygen that is pumped into the lake?

c. Which source of oxygen to the lake is the most significant in governing changes in the lake's total oxygen.

Water Level Management: Findings

Based on the data available for this study, it appears that maintaining the water level of Charleston Slough at a level of approximately 100 MVCD has little impact on the stability of DO in Charleston Slough. Though the water level has been maintained near that level since the fall of 1989, the extreme diel and seasonal DO cycles have continued to occur. The author hypothesizes that DO levels in the slough were not in fact stable at any time since monthly testing began in 1986, but that the infrequent schedule of testing was not adequate to uncover the typical extreme variations which naturally occur in the slough as it is now constituted.

Time of Day of Pump Operation: Findings

Pumping on a 12:00-24:00 h schedule rather than a 7:00-19:00 h schedule delivered significantly more oxygen to the lake during the months from April to November, 33% more per day on average. During the winter from December to March, apparently the time of day of pumping did not have a great impact on the amount of oxygen delivered to the lake because DO did not drop below the 5.0 mg/l standard during these months at any time.

Comparison of Oxygen Input to Lake from Various Sources: Findings

Based on the few days when complete data sets were available at the SML–1 and SML–2 stations in the lake, apparently the daily photosynthesis/respiration and reaeration cycles in the lake have the most significant impact on daily changes in total oxygen in the lake during the summer months. On average these factors were responsible for 89 % of the total oxygen change in the lake during the 12 hour period beginning at 8:00 h, the time corresponding to the approximate hours when photosynthesis occurs during the summer.

Possibilities for Further Research

Anaerobic Conditions in Diked Wetlands

Monroe and Kelly (1992, 17) stated that, in general, low oxygen and high nutrient levels are not considered to be adversely affecting beneficial uses of the San Francisco Bay estuary. However, they also state that the South Bay is the 1 part of the bay where there is a potential for problems. The results of this study indicate that in a diked wetland area in the South Bay, there are adverse conditions affecting beneficial uses due to high nutrient loadings that lead to anaerobic conditions. Further research is needed in other similar environments around the bay to determine if anaerobic conditions are still more widely prevalent than previously thought.

Diel Nutrient Cycles

Welch (1980, 66-75) discussed research findings that under anaerobic conditions, the substrate releases both nitrogen and phosphorus compounds into the overlying waters at a much greater rate than under aerobic conditions. In an experiment with deposits taken from an area where there had been increased sedimentation due to sewage treatment plant outfalls over an approximately 40 year period, it was found that the rate of release of phosphate phosphorus to the water column under anaerobic conditions increased from 1.7 to 14.0 mg/m^2/day and that of ammonium nitrogen increased from 0.0 to 73.0 mg/m^2/day compared to aerobic conditions.

Since anaerobic conditions routinely occur in Charleston Slough during the summer and fall months during the morning, nutrient concentrations in the slough water column may undergo large variations on a diel cycle during that time of year. It may be that the 12:00-24:00 h pumping schedule significantly reduces the nutrient loading to the lake compared to the 7:00-19:00 h schedule at that time of year. To test this hypothesis, further testing would be required because existing data on nutrients in the lake and slough are sketchy and were not collected with regard to time of day.

Systematic nutrient data could lead to a nutrient budget study of the lake which then could be used to determine what may be the most appropriate techniques for nutrient reduction (Cooke et al. 1986) in the lake that would help restore and maintain the lake water quality at acceptable levels.

Community Metabolism

The diel oxygen data used for this study could also be used to calculate rates of community metabolism for photosynthesis and respiration in the slough and the lake if an appropriate reaeration constant was found to account for the oxygen change due to reaeration. There have been numerous empirical formulas developed to calculate reaeration constants under different conditions (Bowie et al. 1985), but research would have to be done in the literature to determine which of these formulas would be appropriate to the conditions at Shoreline.

Restoration of Charleston Slough to Salt Marsh Habitat

The results of this study will serve as a baseline for study of the water quality changes that will occur when Charleston Slough is modified to restore it to a salt marsh. How will increased tidal action in inner Charleston Slough affect the diel and seasonal DO cycles in the slough and the lake? Will modifiying Charleston Slough have a positive impact on the lake's water quality? These questions should be addressed as a part of the monitoring plan implemented to determine the effects of the Charleston Slough restoration project.

Recommendations for Lake Management

Harvesting Aquatic Plants

An early report of water quality conditions at the Sailing Lake (Axler, Goldman, and Reuter 1984) recommended that Shoreline routinely remove attached algal blooms and weeds that may occur in the lake from time to time in order to reduce nutrient inputs to the lake and to remove organic matter that would increase BOD when it decayed. To the author's knowledge such a plan has never been implemented in the lake except on a sporadic basis.

At the pump, algae are removed from the grating in front of the pump on a routine basis and dumped by the shore where they are left to decay.

Periodically these piles are removed from the site, but not before they have decayed considerably.

Since high nutrient loadings from the bay waters are a normal aspect of being so near the PARWQCP, the only practical way to reduce the nutrient load in the lake and the slough as long it is not subject to tidal action is to implement a regular plan of removal of excessive algal growth in both the slough and the lake. Research would need to be done to find the most suitable techniques and to estimate the costs to see if such a plan is economically as well as practically feasible.

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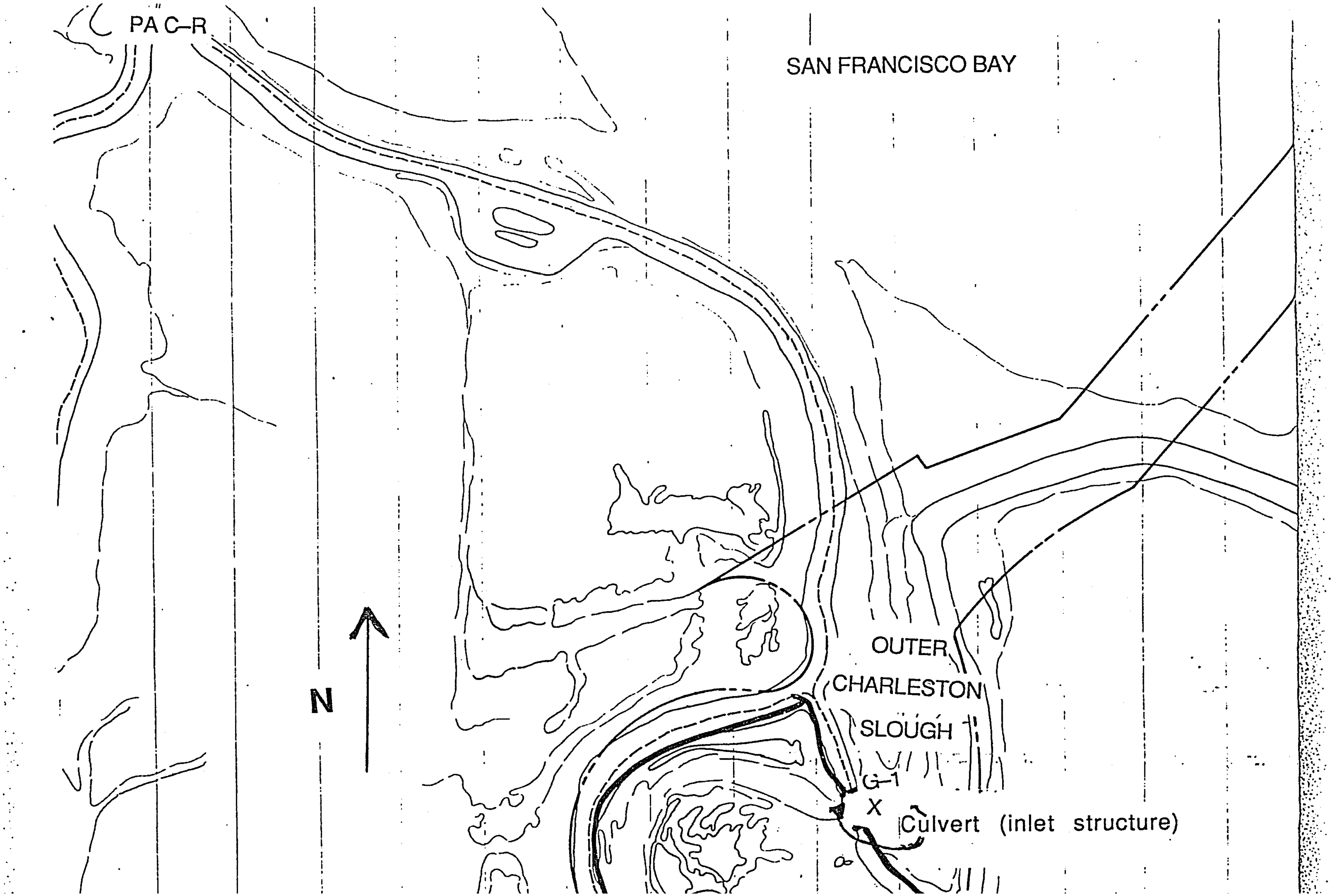
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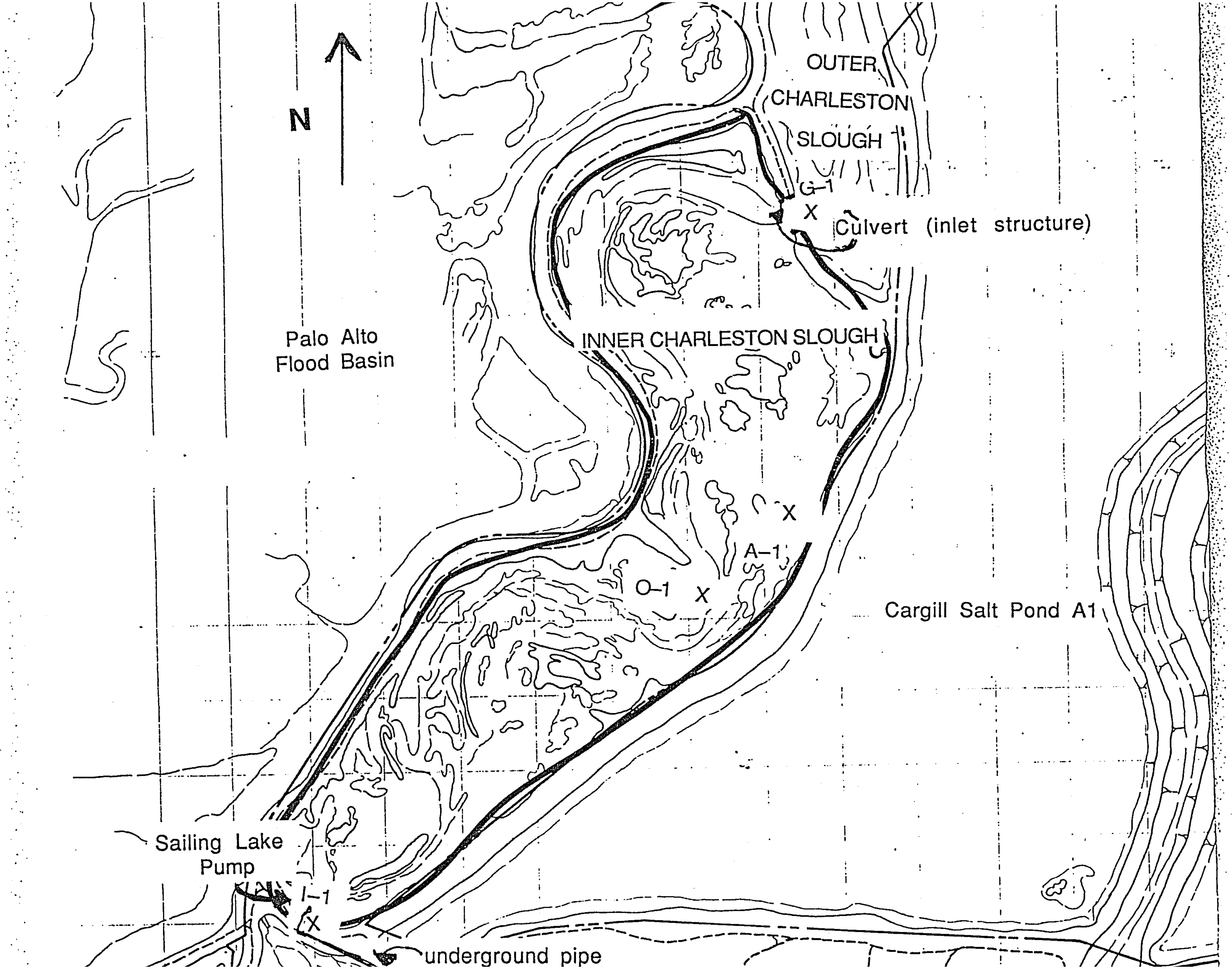
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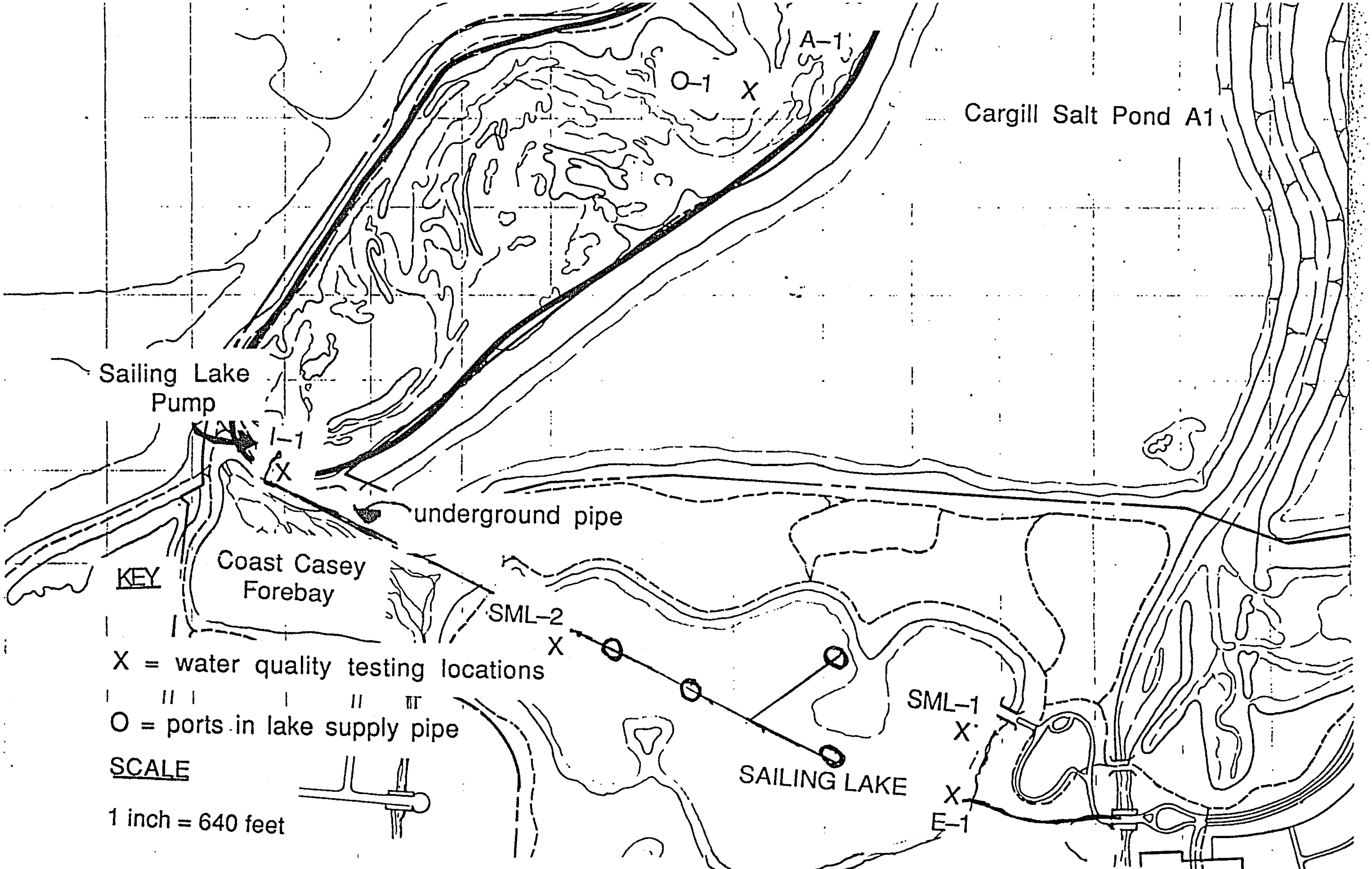

Fig. 2. Map of study area. Adapted from unpublished map of Shoreline at Mountain View supplied by Shoreline staff.